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The relation of the structural evolution of the Macquarie syncline to sedimentation in the Moon Island beach sub-group, New South Wales

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THE RELATION OF THE STRUCTURAL EVOLUTION OF THE MACQUARIE SYNCLINE TO SEDIMENTATION IN THE MOON ISLAND BEACH SUB-GROUP, NEW SOUTH WALES

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CONTENTS

ABSTRACT

In the Macquarie Syncline and a number of other areas of the Sydney Basin there is an apparent relationship between the thickness of some formations and the present-day structure of the Basin. Trend-surface analysis of borehole information has been used to quantitatively analyse both the structure and thickness data of the Moon Island Beach Sub-group into regional and local components. The vertical variation of the Sub-group has been analysed using Markov Chain analysis.

The structure of the Macquarie Syncline may be resolved into two simple regional components: one, a planar homoclinal dipping to the southeast, and the other a synclinal component striking northnortheast. Local structural components isolated as residuals from the structure trend-surfaces correspond with prominent ridges and depressions along, and adjacent to, the Macquarie Syncline.

The thickness data for fourteen consecutive units in the Moon Island Beach Sub-group when analysed into their regional and local components yield results which may be grouped according to the lithology and geographic extent of each formation. The widespread coals reveal a planar increase in thickness to the northeast with superimposed antiform thickness trends with axes striking northnortheast and coinciding with the synclinal component of the Macquarie

Syncline. Similar results are obtained for the fine clastic horizons. Linear correlation between the structure residuals and the thickness residuals also shows a statistically significant inverse correlation at a local scale. The conglomerate and sandstone formations do not always show consistent regional or local patterns of thickness variation.

These results indicate that the present structure, apart from the homoclinal dip, is a simple intensification of a persistent basement subsidence pattern which prevailed during the late Permian. The degree to which the thickness variations reflect the tectonic subsidence is governed by the rate of accumulation of particular lithologies. Slowly accumulating coal seams best reflect the tectonic subsidence geometry, while conglomerates were only slightly influenced by tectonic subsidence. Compactional subsidence of the substrata was probably more important in determining the geometry of the coarse clastic formations.

CHAPTER 1

INTRODUCTION

In the Sydney Basin a general relation appears between present-day structure and the thickness variation of some late Permian and Triassic formations. Various workers (e.g. Raggatt, 1938) over the past eighty years have made observations supporting this hypothesis; it has been disputed by others (e.g. Duff, 1967). The aim here is to examine the thesis that present-day structure is essentially synonymous with Permian basin structure and has determined both regional and local variations in the accumulation of the sedimentary succession. To enable a rigorous evaluation of this structural control of deposition, detailed, accurate regional data extending over a significant increment of time are necessary. Various mathematical and statistical methods of analysis have been applied to such data to evaluate the relationship between structure and sedimentation.

1.1 TECTONIC FRAMEWORK OF THE SYDNEY BASIN

The Sydney Basin is a large epicontinental basin which formed towards the end of the Palaeozoic Era between two adjacent geosynclinal fold blocks (Fig. 1.1). To the north the New England Geosyncline is thrust against the thick Permian sequences of the Hunter Valley. West and south, and

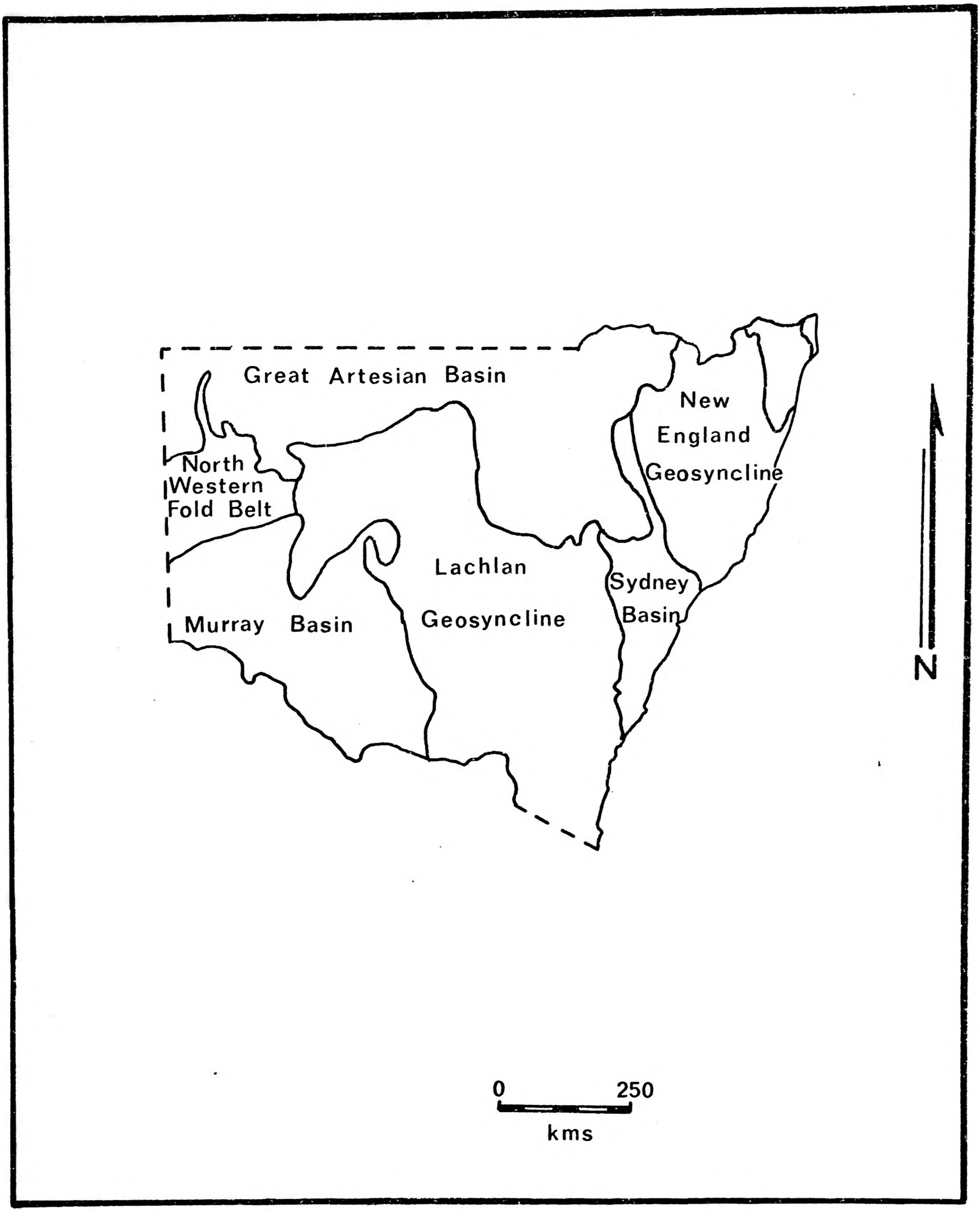

FIGURE 1.1 Tectonic relationship of the Sydney Basin.

apparently underlying much of the basin are rocks of the Lachlan Geosyncline. The Lachlan Geosyncline behaved essentially as a craton after the Middle Carboniferous but the New England Geosyncline was still active during the Permian. Both of these geosynclines are part of a large orthogeosynclinal province which existed along the eastern part of Australia during Palaeozoic times. This zone is generally known as the Tasman Geosyncline. To the east the structural limits of the basin are unknown. The narrow continental shelf zone along the N.S.W. coast would seem to indicate a sheared continental margin and hence the eastern limit of deposition in the Sydney Basin is conjectural. Some workers (e.g. Brown *et al.*, 1968) suggest that the Sydney Basin sediments are a "molasse" stage of the late Palaeozoic New Zealand Geosyncline which may have been related to the elevation above sea level of part of the New England Geosyncline.

Material was eroded from these older Palaeozoic blocks to the north, west, and south, into a broad, shallow north-south trending depression. Early and middle Permian deposition was shallow-marine with minor, but significant phases of glacigene sedimentation (diamictites) and restricted periods of coal measure deposition. Widespread non-marine coal measure sedimentation occurred towards the end of the Permian. Thick freshwater Triassic sediments blanket most of the older sediments in all but the eroded margins of the

Sydney Basin. The full Permo-Triassic succession has a maximum recorded thickness slightly less than 4,000 metres (12,000 ft) near the centre of the basin in the Broken Bay area.

The present structure of the basin may be visualised as an elongate saucer-shaped "depression" dipping gently in towards the basin centre from all sides and tilted slightly to the east (Fig. 1.2). The relationship between structure and thickness at this scale is obvious: generally the sequence is much thicker in the centre of the basin than in the peripheral outcrop areas. Superimposed on this basin structure are a series of northerly trending broad fold-like structures which are best developed in the north. These structures are of interest in this study. Many of these structures have been considered by many workers (e.g. Browne, W.R., 1933; Raggatt, 1938) to have formed during the late Tertiary Kosciusko "Orogeny" as a result of broad epirogenic movements across Eastern Australia. Others have been related to the Permo-Triassic (Raggatt, 1938) Hunter-Bowen Orogeny in the New England Geosyncline. General uplift of the basin may have occurred in the Late Tertiary, but this work and that of Cook (1969a,b) would indicate that most of the structures were present at the time of deposition and that the Kosciusko "Orogeny" did little more than perhaps intensify them. Although the usage of descriptive fold names such as the Kulnura Anticline may have been made in the past with ill-defined

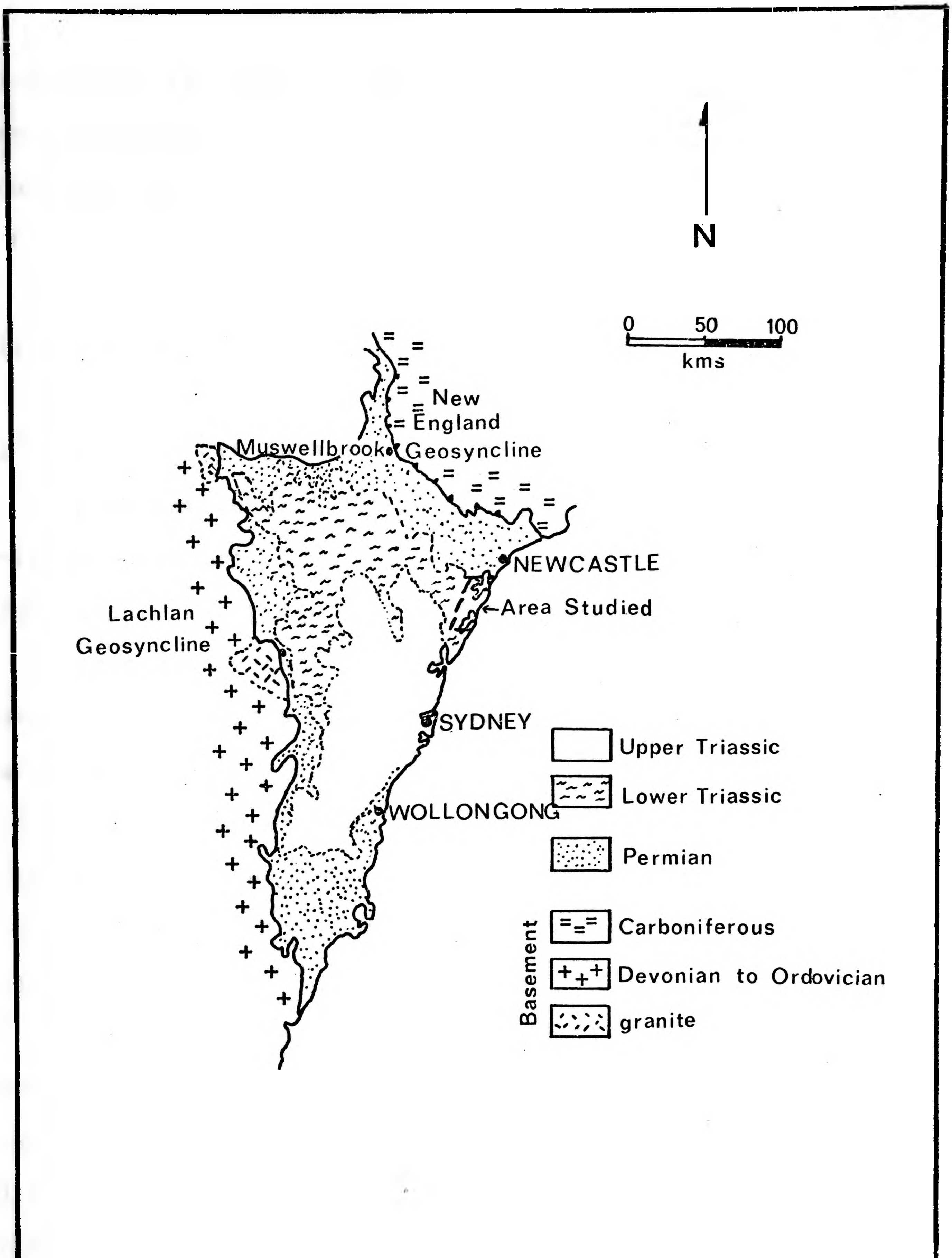

FIGURE 1.2 Regional geology and structure of the Sydney Basin

connotations it is convenient to continue their use remembering that they only describe the general form of the structural surface. There should be no inference as to the mechanism of their origin.

Further discussion of the structure of the basin in relation to these 'folds' is given in Chapter 2.

1.2 STRATIGRAPHIC DATA

Any objective analysis of structural and thickness variations requires accurate and detailed stratigraphic information. Except for the margins, data on Permian rocks are sparse and is confined almost solely to the economic coal measures. The main source of information is from the numerous coal bores in areas of shallow cover. For this reason, and because of the importance of any possible structure-thickness relationship to coal mining and prospecting, diamond drilling data on fully cored boreholes were selected as suitable for detailed analysis.

At the time of commencement of this investigation there were a number of areas where regional drilling programmes had been recently completed. These included areas in the Southern and Western Coalfields, as well as the Newcastle and Hunter Valley Coalfields. Data from the Hunter Valley where large-scale open-cut operations were proposed in some localities, were considered too clustered and structurally selective. Extreme correlation problems in parts of the Hunter Valley would also lower the reliability of any analysis of data from this area. Western Coalfield data again lack even coverage and the area may not be structurally representative of the main basin. The Western Coalfield lies to the west of a major monoclinal structure, the Lapstone Monocline, which runs parallel to the western margin of the basin. Results from this area may not necessarily be applicable to the rest of the Sydney Basin.

A major exploration programme had recently been completed by the New South Wales Mines Department across the Southern Coalfield. Although bores sunk in this programme have sufficient vertical detail in terms of the number of formations penetrated, the density of drilling was only on approximately 4 km spacings, and hence there was a lack of close areal control. Further the absence, for many bores, of accurate survey information on collar location and level, would have introduced an intolerable source of error into the statistical methods used to analyse the data.

Structurally the Southern Coalfield during the Permian seems to have been a far more stable environment than the central and northern part of the basin. This interpretation is suggested by the fairly simple and relatively thin succession of the Illawarra Coal Measures. The Mines Department drilling programme outlined an east-west hinge-zone across the northern part of this coalfield and Bunny *pers. comm.* observed a concomitant increase in the thickening rate over this hinge line. Although data on palaeocurrent directions and source areas are sparse it is generally agreed that the bulk of clastic material deposited during the early Triassic was derived from the north. Clastics were also derived from the south and west in the Illawarra Coal Measures, as evidenced by the abundance of locally derived basic volcanic detritus in the sandstones of these coal measures. This volcanic detritus becomes less prominent to the north presumably due to dilution with material from the north. Environmentally the Southern Coalfield, especially to the south of the hinge zone, may differ from that in areas to the north of the hinge. The reasons, however, for not using these data were largely poor control in spacing and inaccuracies in the bore surveys.

The area that was selected as being most suitable is to the south of the Newcastle Coalfield in a region where, since 1960, more than one hundred and fifty bores have been sunk over an area of approximately five hundred square kilometres (200 square miles). The drilling has been carried out by the Electricity Commission of New South Wales and several coal mining companies for the purpose of delineating reserves of coal for power generation. The bore spacing varies from approximately 1 km to 3 kms with clusters of bores within colliery holding areas. The drilling covered sufficient area to be of regional interest whilst having an adequate bore density to provide accurate local stratigraphic control. The succession of economic interest is the Moon Island Beach Sub-group, the top sub-group of the Newcastle Coal Measures. The Sub-group contains a number of thick widespread bituminous coals of low-medium rank and a relatively low vitrinite content. They tend to have a high inorganic content (approx. average of 20%). These coals are mined over much of the area as feed for the three local power stations.

The area may be identified structurally with the north-eastern margin of the Sydney Basin with the general regional dip being south-southwest towards the basin centre. The clastic sediments within the Sub-group (conglomerate, sandstones, and claystones) were apparently derived from the north, as indicated by the southerly trending foreset dip directions and the geometry of individual coarse clastic lithosomes. The Newcastle Coal Measures in the immediate Newcastle area appear to have been deposited in a more active structural environment than that prevailing to the south. In the southern extension of the Macquarie Syncline south of Wangi Peninsula, the Newcastle Coal Measures are less complex and were probably deposited under a less rapidly subsiding environment. The Moon Island Beach Sub-group has sufficient vertical detail in the stratigraphy with between three and seven coal horizons present, and three different interseam clastic lithologies. The Sub-group has a maximum recorded thickness of approximately 150 metres. This thickness is adequate to permit a study of the variation in time of structure-thickness relations and permit some distinctions to be made concerning the nature of local thickness variations i.e. whether they are caused by persistent contemporaneous structures or ephemeral differential compaction-induced structures.

1.3 METHODS OF ANALYSIS

The most obvious manifestation of any active contemporaneous structural control on the local and regional deposition will be the thickness variation of individual rock units. An active structural environment may not necessarily be revealed overtly in the thickness of a given unit especially if regional transgressive-regressive influences are dominant, or if deposition is excessively rapid. Also, severe diagenesis may modify the sediment and destroy an original thickness pattern. Where such events may have occurred other methods relying on the petrology of the sediments may be needed to establish whether any structural control was present and has been preserved.

Given that it is axiomatic that clastic deposition and continued peat accumulation is initiated by subsidence and will be controlled by the rate of subsidence, areal thickness variations immediately subsequent to deposition should be a reflection of the regional and local subsidence. After deposition and compaction of the sediments, both large and small-scale deformations will occur which may not be related to the structural environment controlling the sedimentation. The present-day structure of a basin is the net effect of the super-imposition of both the contemporaneous structure and the post-depositional deformation.

In this study one of the aims is to analyse the present basin geometry into the components of the Permian basin structure, by assessing the relation of structural elements to overall thickness patterns and the geometry of individual lithosomes, as well as the post-Permian modifications caused by later stress fields. These subsequent effects will, to a large extent, be revealed as a deviation of the present structure from the expected Permian structure. Both the thickness and structure of a particular unit will have local and regional components of variation and as these are likely to have different effects it is necessary to attempt to isolate these components.

Trend-surface analysis is a mathematically based method which provides an objective resolution of any mappable (geological) variate into two sensible components (Krumbein, 1959; Harbaugh & Merriam, 1968): one, the trend-surface, being analogous to the regional variation, with the other, the residual map, corresponding to the combined effect of meaningful local variations and random 'noise' in the data (Krumbein & Graybill, 1965). Local variations relate to areas smaller than those showing the regional patterns, and are delineated by a number of adjacent points having correlated deviations.

The mathematical methods used are discussed in detail in Chapter 3. Brief outlines are given here for introductory purposes. The analysis is performed by considering the geographic grid location of each data point as the independent variables and the value of that data point (e.g. thickness of a lithosome) as the dependent variable and performing multiple non-linear regression on the data to obtain a family of best fit surfaces. These surfaces belong to a simple polymonial power-series expansion and are generally fitted using the least-squares criteria (i.e., sums of squares of the deviations from this surface are minimised). The model used is:-

$$Z = A + Bx + Cy + Dx^2 + Exy + Fy^2 + \ldots$$

where

Z = dependent variable: thickness, assay, structure level

x = independent variable: easting

y = independent variable: northing

$A, B, C, D, E, F \ldots$ = coefficients

The linear or first-degree surface is simply a plane of best fit through the given Z values, and the quadratic (second-degree) surface is a curved paraboloid surface. The surfaces then become progressively more complex as further terms in the above expansion are added. Certain surfaces may be considered as meaningful approximations to the large-scale regional component in the data, e.g., the planar surface may represent a homoclinal dip element. Both statistical and geological controls are used in determining which of the series of surfaces are reliable and useful for further analysis.

The residual surfaces are obtained by subtracting the set of trend-surfaces from the observed values. The residual maps show the local variation in the original data with various patterns of regional variation (the trend-surfaces) removed from the original data. Hence the data may be inspected with, for example, the homoclinal dip component, or some fold element extracted. This generally enhances and accentuates the localised variations in the data.

In this study trend-surface analysis has enabled the structural and thickness data from fourteen consecutive units of the Moon Island Beach Sub-group to be resolved into regional and local components. Such components assist in the recognition of contemporaneous and post-depositional structures and their effect on the accumulation of the sedimentary pile. The analytical approach to the lithosome geometry forms the basis of the environmental interpretation of the deposition in relation to the structure-sedimentation relationship.

Vertical control on the lithological variation has been provided by analysing the sequence of rock types in terms of the possible combinations of types of transitions from one lithology to another. The method used, Markov Chain Analysis, yields characteristic sequences or transition patterns for different successions which appear to be indicative of different depositional environments (Harbaugh & Bonham-Carter, 1970).

These methods are discussed more rigorously in Chapter 3. As they are largely computer-dependent, a discussion of the programs and algorithms used for these analyses and of display programs such as automatic contouring procedures for the rapid production of contour maps generated by the trend-surface analysis, is also included in Chapter 3.

1.4.1 Previous Work - Sydney Basin

The stratigraphy of most of the outcropping rock units in the Sydney Basin is fairly well established. Within the centre of the basin and in outcrop areas of no apparent economic interest, knowledge of the succession is very sparse. Most coal drilling activity has been confined to the basin perimeter in areas of shallow cover (less than 500 m) and only rarely have drill holes penetrated below the depth of economically-mineable coal. A few petroleum exploration wells in the deeper part of the basin have been sunk (without success). As a result, accurate, correlatable data on the basement and the sequence below the upper Permian coal measures are limited and any discussion involved with the basement structure is, in part, conjectural.

Published work on the Triassic and upper Permian strata includes David (1907), Harper (1915), and Carne (1908), on the geology of the coalfields and their work formed the basis of most subsequent investigations. Drilling data in the past twenty years have resolved many stratigraphic problems and will continue to do so. The 'Geology of New South Wales' (ed. Packham, 1969) published by the Geological Society of Australia is the best available synopsis of the stratigraphy of the Sydney Basin and covers all but the most recent modifications to the stratigraphy. Mayne *et al.* (1970) present a thorough bibliography of the published work on the Sydney Basin.

The most relevant and lucid discussion for the work submitted here is however H.G. Raggatt's D.Sc. thesis (1938) on the structural evolution of the Sydney Basin and the Hunter Valley. He was first to suggest that the fold-like structures were not entirely post-depositional and realised some of the implications for the genesis and development of the basin.

The Macquarie Syncline has been studied in detail especially at its northern end in the outcrop areas. In its southern extension (the area studied) the publications are concerned only with recording the stratigraphy. Virtually no studies of the palaeogeography have been undertaken although recently Branagan & Johnson (1970) have attempted an analysis of the palaeoenvironment in the coal succession to the north by conventional methods from bore log information. Blayden (1971) carried out a structural analysis of the Macquarie

Syncline mainly based on joint directions and their relation to the 'folding'.

1.4.2 Previous Work - Mathematical Geology

The application of mathematical techniques to geological data has been continuing in the U.S.A., U.K. and South Africa for over twenty years. Sichel (1947) and Krige (1951) in South Africa applied statistical methods to the Rand gold ores. In Kansas they were applied to oil exploration data and have since penetrated most aspects of geology where numerical data are readily available. Trend-surface techniques were first applied to structure analysis by Krumbein (1959), Whitten (1968), Harbaugh (1963), James (1966), and Merriam and Sneath (1966); the work largely emanated from the North-western University and the Kansas Geological Survey. Work with similar aims to this study i.e., to compare thickness and structure variations has been performed on English coal measure sequences by Doveton (1970), Duff and Walton (1964), and Parsley (1971).

The only work of this kind in the Sydney Basin was by Cook (1969a,b) who compared the structure and thickness of the Bulli Coal in the Southern Coalfield using trend-surface methods. This thesis forms a logical extension of this work. Work by Johnston and Cook (1969) on the relation between analytical coal parameters and local structure over two colliery holdings (approx. 40 sq. kms) in the same area is also relevant to this work.

CHAPTER 2

STRUCTURE AND STRATIGRAPHY OF THE SYDNEY BASIN

2.1 INTRODUCTION

The Sydney Basin contains a succession of relatively undeformed Permian and Triassic strata and is defined as a separate structural element situated between the two Palaeozoic fold blocks of N.S.W. (Fig. 1.1). The New England Geosyncline was still active in lower Permian times; the Sydney Basin downwarping of part of the adjacent and now stable Lachlan Geosyncline resulted from thrust movements (Rose, 1967) along the southern flanks of the New England Geosyncline against the new craton. These thrust movements persisted at least until the Hunter-Bowen Orogeny which began probably in middle-late Permian time. They are now manifest as the Hunter Thrust System which forms the northern boundary of the Sydney Basin except in the northeast portion where no definite boundary can be recognised. In some parts of the Hunter Valley basal Permian sediments overlap sediments of Carboniferous Kuttung Facies with slight angular unconformity (Osborne, 1950). Usually, however, northwest-trending faults of the Hunter Thrust have overthrust the Permian sediments against deformed Carboniferous rocks. The throw has been estimated at approximately 2000 metres with the dip of the thrust planes as low as 30° in places (Osborne, 1950).

The Carboniferous rocks along the northern boundary are composed of acid volcanics, and continental and glacial sediments.They may be regarded as a relative basement for the Permo-Triassic rocks in the northern part of the basin. Along the western and southern margins of the Sydney Basin Permian sediments lie on folded Lower and Middle Palaeozoic sediments and granites of the Lachlan Geosyncline. Although the Sydney Basin is described here as a structural entity, Permian and Triassic sediments extend to the northwest and pass into the Oxley Basin, a southeastern attenuation of the Great Artesian Basin (Packham, 1969) and thin Permian successions probably extended well to the west of the present limits imposed by erosion.

2.2 BASIN STRUCTURES

The general basin shape and tectonic framework of the basin have already been described above and in Chapter 1. North-south trending fold-like structures are superimposed on the general basin structure, one of which, the Macquarie Syncline lies within the area which forms the basis of the present study. These structures tend to become faulted near the Hunter Thrust System and some are slightly deflected towards the northwest close to the Thrust zone. Figure 2.1 shows the location of these structures in the basin and the names of the more important 'folds'.

The Lochinvar Anticline (David, 1907) is the most

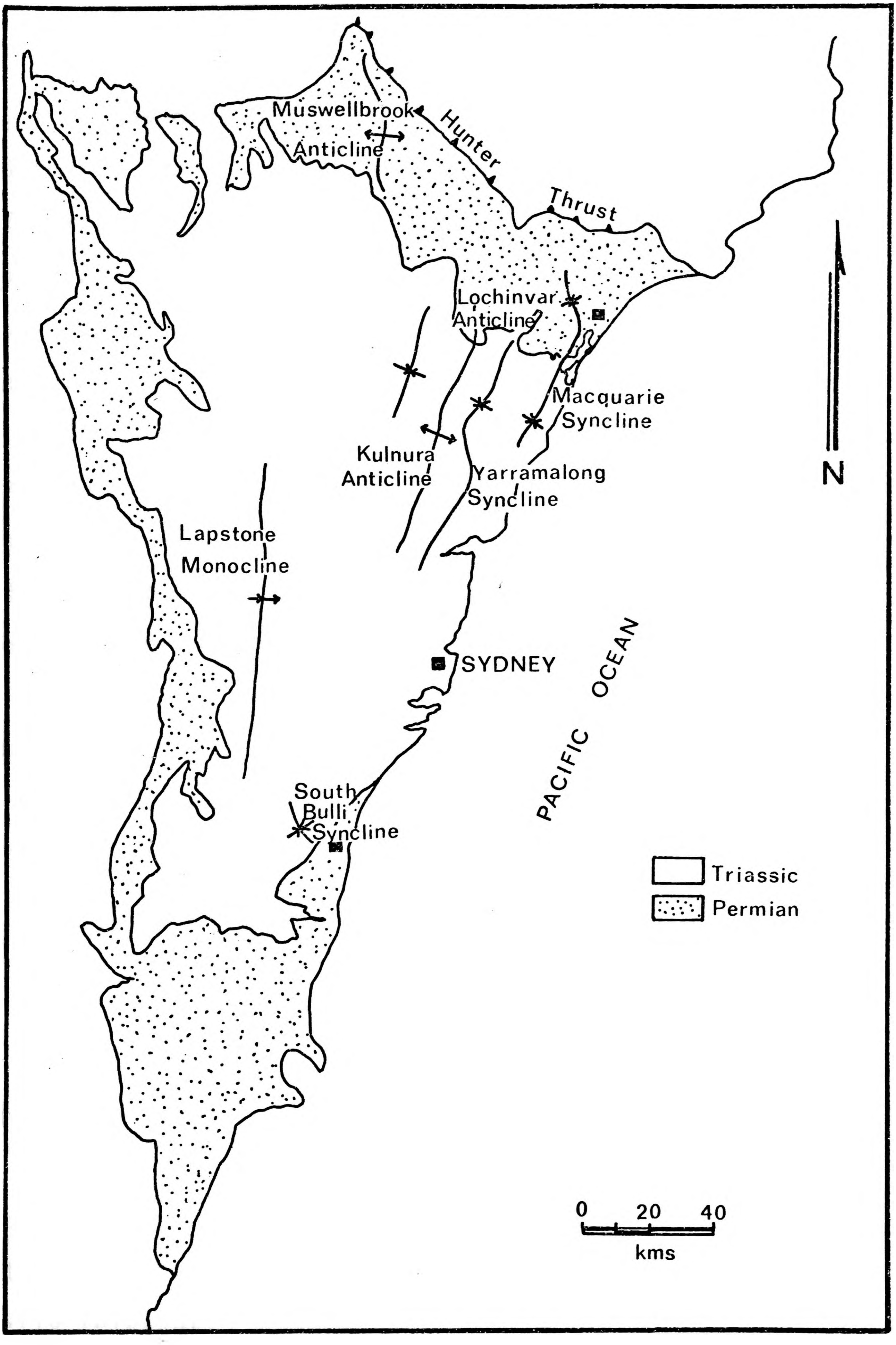

FIGURE 2.1 Prominent basin structures in the Sydney Basin

prominent of the structures in the Hunter Valley. It lies some 15 kms to the west of Lake Macquarie and trends slightly east of north and more or less parallel to the Macquarie Syncline. During the Late Permian the Lochinvar Anticline was obviously mobile and formed a rising, outcropping structure (Rattigan & McKenzie, *in* Packham, 1969); the Newcastle and Singleton Coal Measures thin rapidly towards the structure and are absent across the crest in the Cessnock district. The Kulnura Anticline, a southerly extension of this structure, some 30 kms south of Cessnock in the Kulnura Bore, has a thin coal sequence across the crest which indicates that although it was still active, the intensity was not as great as further north near the Hunter Thrust System. To the immediate east of the Lochinvar-Kulnura Anticline is the Yarramalong Syncline (Raggatt, 1938). This, in turn, is separated from the Macquarie Syncline by a less marked and unnamed anticlinal rise. This is named here as the Morisset Anticline.

2.3 REGIONAL STRATIGRAPHY

In this section the regional stratigraphy of the Sydney Basin, with emphasis on the Hunter Valley area, is discussed. This stratigraphy is summarised in Table 2.1. Details of individual formations within each group are given only when especially relevant.

2.3.1 Dalwood Group (David, 1907)

These are probably the oldest Permian rocks in the Sydney

HUNTER VALLEY	WESTERN-SOUTHWESTERN MARGIN	SYDNEY DISTRICT	SOUTH COAST
Narrabeen Group	Wianamatta Group Hawkesbury Sandstone Narrabeen Group	Wianamatta Group Hawkesbury Sandstone Narrabeen Group	Wianamatta Group Hawkesbury Sandstone Narrabeen Group
Newcastle Tomago Singleton Coal Measures	Illawarra Coal Measures	Illawarra Coal Measures: Sydney Sub-Group Cumberland Sub-Group	Illawarra Coal Measures: Sydney Sub-Group Cumberland Sub-Group
Maitland Group	Shoalhaven Group	?Shoalhaven Group	Shoalhaven Group
Greta Coal Measures Dalwood Group			Clyde Coal Measures
Carboniferous	Carboniferous granite; older Palaeozoic rocks	?Carboniferous	Devonian and Ordovician rocks

TABLE 2.1 Generalised stratigraphy of the Sydney Basin.

Basin. They are a thick (1800 m) sequence of pyroclastic and volcanic rocks and marine sediments and while the Group and its correlatives are widespread in the Hunter Valley the southerly subsurface limits are unknown (Osborne, 1949; Rattigan, 1969 *in* Packham, 1969). However the sequence thins rapidly towards the Hunter Thrust System and probably to the south. The lower part of the sequence (volcanics, pyroclastics and lithic sandstones) was deposited in the incipient structural furrow that developed in association with the early movements of the New England Fold Block against the (now stable) Lachlan Geosyncline. Subsequently more widespread marine clastic deposition occurred as the main basin structure developed and became more pronounced.

2.3.2 Greta Coal Measures (David, 1888)

This is a fresh-water sequence of fine conglomerates (av. size 1 cm, max. 5 cm), sandstones, siltstones, shale and bituminous coals (Basden *in* Packham, 1969). The rocks outcrop mainly around the Lochinvar and Muswellbrook Anticlines but detailed correlation between these two areas is not possible. To the west in the Muswellbrook area there is an overall decrease in grain size in the clastic sediments. Southwards the Greta Coal Measures pass laterally into marine sediments (Mayne *et al.*1970). No equivalents in the Southern and Western Coalfield are recognised. The thickness is approximately 60-75 metres in the Lochinvar Anticline area and

200 metres at Muswellbrook. Thicknesses of up to 400 m have been recorded by Booker (1953) in the Cranky Corner Basin, an outlier of Permian sediments to the north of the Hunter Thrust.

The coal seams, which are commonly thick (> 10m), are of low rank and generally have low ash yields, but a high sulphur content (both organic and pyritic).

2.3.3 Maitland Group (Booker & Hanlon, *in* Hill, 1955)

This group was deposited during a major marine transgression which extended over the entire area of the basin. The sequence consists of 1200 m of sandstone, siltstone and conglomerate; it is often richly fossiliferous (McKellar, *in* Packham, 1969). Two formations are recognised.

The Branxton Formation (980m) consists of dark grey sandstones and conglomerates with varying amounts of (?)glacial erratics. The pebbles and erratics average from 2mm to 3 cm in diameter but boulders up to 9m across are distributed through the sequence. An ice-rafted origin has been suggested for the coarse material in the diamictites due to its angularity and the diverse lithologies (granite, lavas and metamorphics). Faunas include spiriferids, productids, fenestellids and bivalves; corals and crinoids are locally common.

The Mulbring Siltstone overlies the Branxton Formation and underlies the Tomago, Newcastle (Lower Hunter Valley) or Singleton Coal Measures (Middle and Upper Hunter Valley), except towards the flanks of the Lochinvar Anticline where it is overlain by the Triassic Narrabeen Group. It has an estimated maximum thickness of 330m on the southeast side of the Lochinvar Anticline. Dark grey siltstone is the dominant lithology although minor limestone horizons are present. The Muree Sandstone Mb. at the base of the Mulbring Siltstone is a prominent mapping unit in the Cessnock area. The Muree Sandstone Mb. apparently shows thickness variations of a different character to the overlying sediments (Raggatt, 1938). The Mulbring Siltstone is probably a lithological correlative of the Berry Formation of the Southern and Western Coalfields.

Across the Lochinvar Anticline, the Mulbring Siltstone, the Tomago and Newcastle Coal Measures are absent. David (1907) suggested that these were removed by uplift and erosion prior to the Triassic. Raggatt (1938), on the other hand, suggested that the Lochinvar Anticline was a rapidly rising structure in the Upper Permian and deposition did not take place. The apparent absence of thickness and lithofacies variations in the Lower Permian across the structure has lead some workers (e.g. Branagan, 1962; and McKellar, *in* Packham, 1969) to infer that the Lochinvar Anticline is an entirely post-Dalwood structure. The Maitland Group is the last major marine transgression of the Sydney Basin.

2.3.4 Tomago Coal Measures (David, 1907)

These overlie the Maitland Group. They have been studied by Robinson (1963) and subdivided into three formations with an estimated total thickness of 1200m. On the eastern flank of the Lochinvar Anticline they are overlain by the Newcastle Coal Measures but to the west of this structure sediments of equivalent age to the Tomago and Newcastle Coal Measures have been grouped as the Singleton Coal Measures. Correlation between these two is not possible. No upper Permian coal measures crop out across the crest of the Lochinvar Anticline in the Hunter Valley. Blayden (1971) has recognised a slight unconformity within the Tomago Coal Measures on the eastern flank of the Lochinvar Anticline. The existence of this unconformity tends to support the idea that the Lochinvar Anticline became active during the late Permian.

The sediments are mainly shales, siltstones and fine sandstones with a number of coal seams present. Rapid facies changes in the clastic sediments makes correlation difficult. Correlation with the rest of the basin is conjectural. To the south and in the centre of the basin in deep bores, equivalent horizons have been postulated (e.g. Stuntz, 1969). Overall the sequence is relatively barren of coal, the main coal horizons being confined to the middle portion of the Four Mile Creek Formation (Robinson, 1963).

A northern development of the Tomago Coal Measures also occurs north of Newcastle in an area referred to as the Port Stephens Basin. The outcrop is obscured by coastal alluvium.

2.3.5a Newcastle Coal Measures (David, 1907)

The Newcastle Coal Measures form the uppermost part of the Permian in the northeastern part of the basin in the Newcastle area. They are best developed along the axis of the Macquarie Syncline where the total thickness ranges from about 70m to in excess of 460m. McKenzie (1962) subdivided the measures into four sub-groups. The subdivision is based largely on economic grounds (see below) and although it appears to have no apparent lithostratigraphic justification it is not the purpose of this thesis to modify or criticise the sub-division. The sequence is best known in the immediate Newcastle area. South of Lake Macquarie information on the lower three sub-groups is sparse. However, these lower units may still be identified as far south as Terrigal (50 kms south of Newcastle) where they are 270m thick. It is possible to correlate most of the major coal seams with reasonable confidence over this distance. The sediments dip gently to the south from the outcrop areas around Newcastle and 35 kms to the south they are covered by 550m of Triassic Narrabeen Group strata. They continue to dip south towards Sydney but south of Sydney they rise gradually to the surface again in the Wollongong region where an equivalent unit is termed the Illawarra Coal Measures. No satisfactory correlations between the northern and southern coal measures have been made; many workers (e.g. David, 1907; Hanlon, 1953; and Smyth, 1966) have attempted to do so on different premises including coal petrography and the petrology of the sediments.

The sediments are conglomerates, sandstones, shales and claystones with coal horizons being fairly abundant. The conglomerates are all similar in composition. They are dark grey in colour and contain cherts, igneous and pyroclastic rocks, and quartzites, all of probable Carboniferous origin, as the predominant pebble type. In fresh exposures occasional green and red cherts give the rock a distinctive appearance although they only account for a minor percentage of the pebbles. The pebbles are well rounded and usually range up to 8 cms with some as large as 15 cms. Their matrix is composed of coarse sandstone with biotite mica being a prominent and ubiquitous minor mineral. A small amount of kaolinitic clay is present. The main cementing materials are calcite, siderite, and quartz but overall they are not well cemented. The conglomerates are often cross-bedded with foresets up to 2m thick being common. The sandstones are usually similar in composition to the conglomerate but have more argillaceous matrix.

The origin and nomenclature of the fine clastic rocks of the Newcastle Coal Measures is somewhat contentious. The rocks are dominately composed of fine quartz and clays (kaolinite and some mixed-layered clays) with fresh biotite mica flakes very common. Their colour varies from light buff to dark brown or green. Some however, are fine siliceous rocks with a cherty appearance. These cherty rocks are usually composed almost solely of silica or of a mixture of silica and analcite (up to

30%) (Loughnan, 1966b). They commonly show contorted and deformed bedding in outcrop and on close examination reveal relict cross-bedding structures. Most workers in the field have referred to these as "tuffs", attributing the presence of biotite and mixed-layered clays to a pyroclastic origin. The biotite is more probably a wholly detrital product of the breakdown of some of the altered white granitic rocks which occur as pebbles in the conglomerates. This material, while too altered for thin section examination, contains approximately 5 to 10% biotite. The presence of mica in the sandstones and conglomerate matrix would seem to indicate that the mica in the fine clastics is not of pyroclastic origin and that normal sedimentary processes of sorting have simply produced a conspicuous concentration of the mineral in the overbank claystones. In any event mica is normally not abundant in pyroclastics.

The cherty rocks containing analcite are considered here to be diagenetically altered claystones and fine sandstones. Under particular chemical conditions, perhaps associated with humic acids derived from the oxidation of vegetation and high cation concentrations resulting from the weathering of lithic material, analcite has developed and crystallised in the interstices of rounded and partly resorbed quartz grains. This replacement of the matrix by well crystallised analcite lead some workers (e.g. Hamilton 1965, Loughnan,1966b) to conclude the analcite was formed as a replacement of glass shards. In

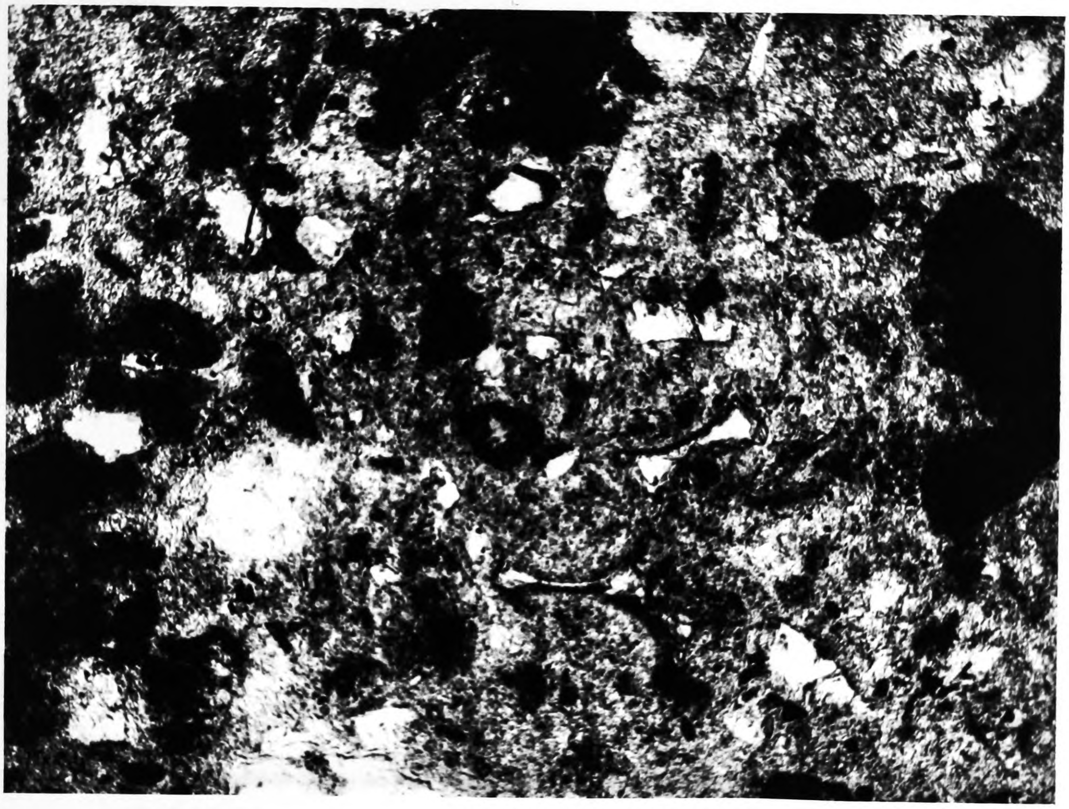

PLATE 2.1a Photomicrograph of "chert" from below Pilot Seam, Swansea. Note analcite "shards". x15

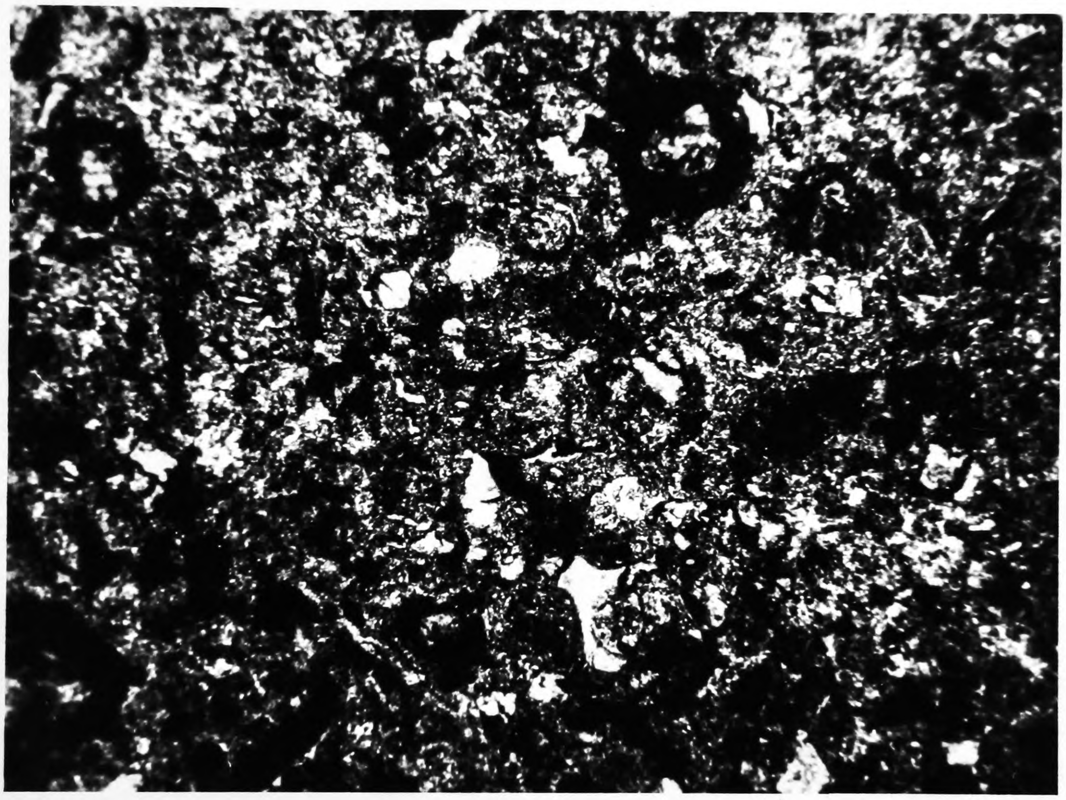

PLATE 2.1b Photomicrograph of sandstone from Eleebana Fm. showing pseudoshards forming with incipient analcite development. x15

fact the "shards" may simply be the interstitial spaces of a compact sand (see Plate 2.1a,b). This recrystallisation of the new mineral in the old sediment has probably caused this contorted bedding (Plate 2.2). These rock types have in the past been and still are termed "tuffs" by some workers. If these rocks are of pyroclastic origin their source is unknown as no contemporaneous upper Permian vulcanism occurs in the Sydney Basin or in the New England Geosyncline. Overall there seems no valid reason to use a genetic term such as "tuff".

The coals are bituminous of medium to low rank (mean maximum oil reflectivity of vitrinite ranges from 0.7-0.9%) with the vitrinite content from ≃ 80% for some of the coals in the lower sub-groups, to 60%-30% for the coals in the Moon Island Beach (Edwards & Cook, 1972). Ash yields (ex-bands) in the lower seams used for coking purposes are from 5-14%, but generally average about 10%. In the upper seams used for steam-raising, ash yields up to 30% occur, but average 12%-18%. The coals are not underlain by distinctive seat-earths with the prominent stigmarian root systems typical of the Westphalian coals and this has been taken by some (e.g. Duff, 1967) to indicate the coals may be allochthonous. However, the coals are invariably underlain by fine clastic sediments containing an abundance of plant remains (esp. *Vertebraria*), and these are probably a seat-earth equivalent. Also there are numerous occurrences of fossil trees ("*Dadoxylon*") in their growth positions extending from the tops of seams into the overlying sediments as well as

PLATE 2.2 Contorted bedding in cherty rocks below the Pilot Seam, Swansea.

'forests' of *in situ* tree stumps in some of the clastic units. Other evidence to support an autochthonous origin is given later in the thesis.

The source area of the detrital material was probably from the north and northeast. Some material could have been derived by reworking of sediments eroded from the Lochinvar Anticline (*vide* the unconformity observed in the Tomago Coal Measures by Blayden (1971)). Along the present eastern margin there is no apparent thinning of the sequence and the eastern limits are unknown. On the coast cross-beds dipping to the west and southwest, and to the east, are common, suggesting that the Carboniferous hinterland extended some distance to the east of the present coast. The conglomerates are most widespread at the top of the section and are up to 90m thick. One unit, the Teralba Conglomerate Member covers an area of at least 400 sq. kms and averages over 30m thick. Local structural deviations due to differential compaction have also been recorded by McKenzie (1962) around the edges of some of the small conglomerate lenses.

2.3.5b Subdivision of the Newcastle Coal Measures

The stratigraphic section of Newcastle Coal Measures is given in Figure 2.2.a.

The basal Lambton Sub-group contains most of the coking coals on which the steel industry of Newcastle is based. The seams are characterised by frequent 'splitting' with wedges of sandstone and some conglomerate separating individual seams.

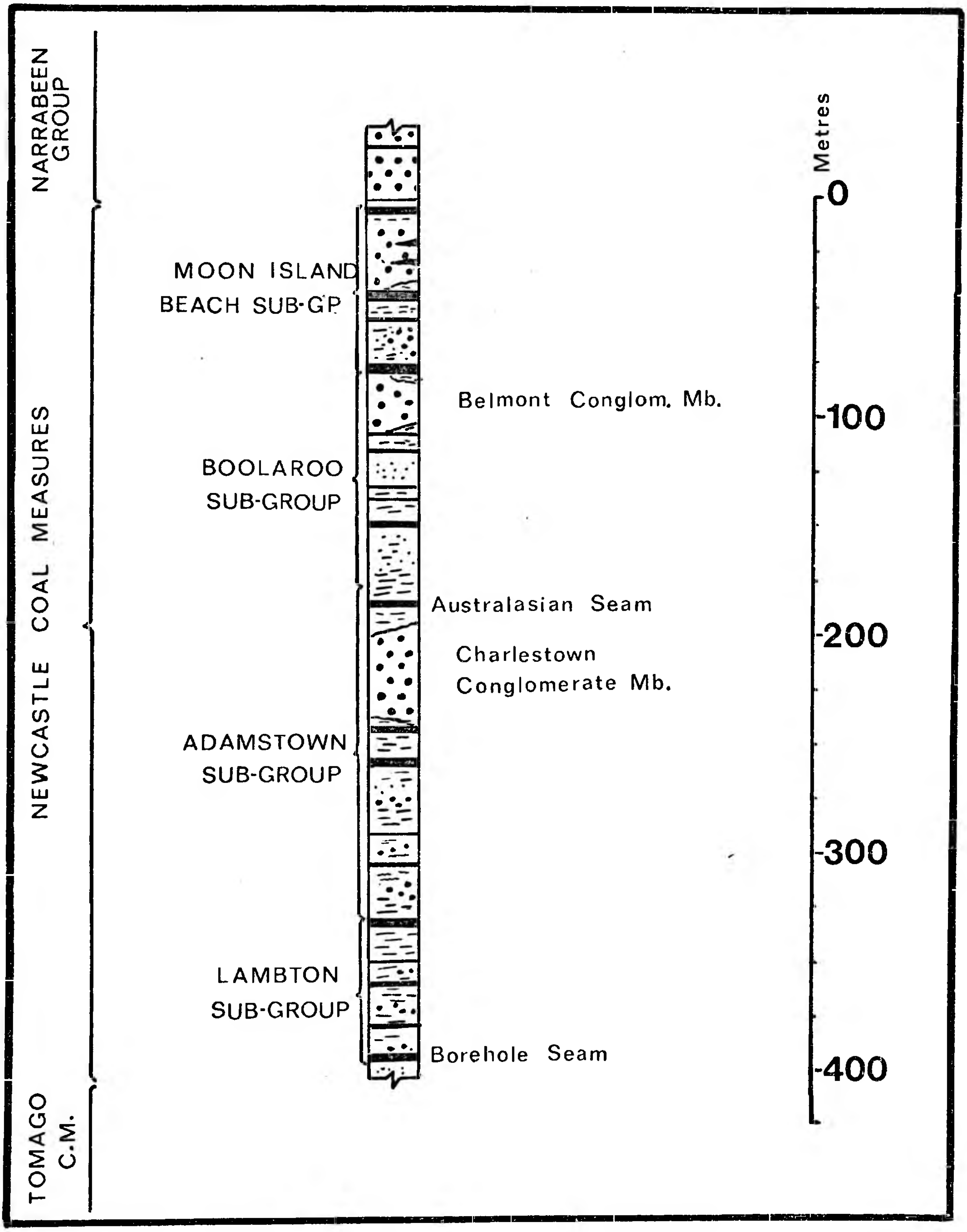

FIGURE 2.2a Stratigraphic column for the Newcastle Coal Measures showing subgroups and formations mentioned in text. (Modified after McKenzie, 1962).

These wedges are probably individual and composite alluvial fans and they tend to be elongate in plan with their long axes in a north-south direction (Branagan & Johnson, 1970). The full section of this Sub-group is exposed along the coast and is over 70m thick. To the west, however, the intervening clastic sediments (mainly sandstones) thin out and the seams apparently coalesce to form the West Borehole Seam (McKenzie, 1962) along the northern extension of the Morisset Anticline. The Borehole Seam in the east has provided an important source of coking coal for over 100 years.

The Adamstown Sub-group which overlies the Lambton Sub-group is up to 170m thick (McKenzie, 1962) contains a number of highly banded coals (e.g. the Australasian Seam) and the first major conglomerate unit, the Charlestown Conglomerate Member (max. thickness 87m). This unit thins rapidly to the west of Lake Macquarie but is still identifiable 10 kms south of Lake Macquarie.

The third sub-group, the Boolaroo Sub-group is composed largely of irregular and highly-banded coals and fine clastic units. The upper formation contains the Belmont Conglomerate Member, another elongate lens of pebble conglomerate which is up to 60m thick.

The Moon Island Beach Sub-group is the uppermost sub-group of the Newcastle Coal Measures. Conglomerate is the main detrital rock type; the three main coals provide extensive reserves of moderate to low vitrinite coal of low bituminous rank and are mainly used for electric power generation. The stratigraphy of this sub-group is discussed in detail below. For convenience the Moon Island Beach Sub-group will hence be referred to in this work simply as the M.I.B.

2.3.5c Structural and Igneous Activity in the Newcastle Coal Measures

The Macquarie Syncline is the main structural feature of the Newcastle Coalfield. It plunges to the south at about 15m to the kilometre along the axis of Lake Macquarie. Blayden (1971) studied the jointing patterns in the Macquarie Syncline and determined five joint directions, the most prominent being in N.W.-S.E. and N.E.-S.W. directions. This worker also concluded that the Macquarie Syncline was formed in Cainozoic time as a result of a slight lateral compression in a W-N.W. and E-S.E. direction. This work is more fully discussed in a later chapter.

The faults which occur in the Macquarie Syncline usually have a throw less than 5m; a few have displacements up to 20 metres and generally strike N.W.-S.E. Some N to N.N.E. striking faults have been found in colliery workings in the area south of Lake Macquarie. They are sometimes in trough patterns (Blayden, 1971). This worker regards the faults as being associated with the same period of deformation as the jointing.

Dykes are the only form of igneous activity in the area. They are concentrated around the south of Lake Macquarie and are in a N.W.-S.E. direction. Individual dykes are seldom more than 2 metres across. They are basaltic in composition and are conventionally assumed to be Tertiary; radiometric dating of these rocks has not as yet been reported. No major sills are known although in some places dykes have locally spread in sill-like extensions into coal seams they intersect.

2.3.6 Narrabeen Group (Triassic)

The basal Triassic unit, the Narrabeen Group is a widespread sequence of quartz-lithic sandstones, red claystones and siltstones, grey shales and fine pebble conglomerates. It has a maximum recorded thickness of 700m in the Hawkesbury-Wyong area (Raggatt, 1938) and it covers most of the Sydney Basin. For the most part it appears to have been deposited from a northerly source with some material being derived from the west and to a lesser extent from the southwest. Recent measurements of foreset dip directions by Goldbery and Holland (1973) support this northerly source as does the abundance of Carboniferous pebbles similar to those found in the Newcastle and Singleton Coal Measures. It conformably overlies Permian Coal Measures across most of the basin except in some poorly mapped areas along the southern boundary, and notably, across the nose of the Lochinvar Anticline where the Narrabeen Group rests unconformably on marine sediments of the Branxton Formation.

Microfloral studies on the Narrabeen Group in both the north and south of the basin by Helby (1966), Hennelly (1958), and Grebe (1970), indicate that the lower part of the section is of Permian age. However, the difficulty in readily recognising the microfloral boundary and the obvious lithological break at the base of the Group has lead to the boundary between the Permian and Triassic being adopted for mapping purposes as the top of the coal measures. This convention breaks down in the area studied where drilling has shown the irregular development of a coal seam (Vales Point Coal Member) above the Wallarah Coal which is generally used to define the top of the Newcastle Coal Measures. This has caused confusion as to the stratigraphic position of the coal-bearing formations above the Newcastle Coal Measures so defined, and is more fully discussed in the proceeding section (2.4).

The Munmorah Conglomerate is the lowest formation in the Narrabeen Group in the N.E. part of the basin; it outcrops over much of the region around and to the south of Lake Macquarie. The lower 85m consists of conglomerates and sandstones and some minor green shales. These are overlain by approximately 150m of sandstones, grey and green shales and some red-green mottled shales. The conglomerates are well sorted with pebbles up to 2 cm. They are finer than the conglomerates of the coal measures and have a larger proportion of matrix. In fresh exposures the conglomerates are light grey whereas those of the underlying rocks are dark grey to grey-green.

The presence of red beds (with up to 25% Fe_2O_3) in the

Narrabeen Group has lead some workers (e.g. Loughnan, 1963) to conclude that the Triassic climate was far warmer than the cool climate that prevailed in the Permian (characterised by the Glossopteris floras, an endemic brachiopod/pelecypod fauna and glacial erratics).

2.3.7 Hawkesbury Sandstone

This is a thick sequence of medium to coarse-grained quartz sandstones and minor interbedded shale lenses. It ranges in thickness from 30m in the Blue Mountains area (western limit) to over 250m in the Hawkesbury-Sydney district. It occupies a smaller area of the basin than the Narrabeen Group and outcrops prominently around Sydney. It is generally conformable with the underlying Narrabeen Group except in the south where it disconformably overlies the Illawarra Coal Measures, the Narrabeen Gp. and part of the coal measures being absent. The sequence is composed of highly lenticular cross-bedded sand bodies with massive laminar-bedded sandstone being uncommon. These individual beds overlap and erode one another resulting in a thick formation of sandstone. The cross-beds are often up to 2m thick and dip to the north and northeast indicating a southwesterly current direction (Standard, 1964). Some of the detrital material may, however, be reworked Narrabeen sediments (Goldbery* *pers. comm.*).

2.3.8 Wianamatta Group

The Wianamatta Group is the youngest preserved phase of

* 1973. University of N.S.W.

Triassic sedimentation in the Sydney Basin. It is a sequence of dark kaolinitic shales and fluviatile sandstones which outcrop over much of the central and southern Sydney Basin. The Group probably was confined to the central and southern portion of the basin as indicated by isopach data (Herbert, 1970). As the sediments are only present as erosional remnants, the full thickness is not known. The maximum recorded thickness of the section is approximately 250m.

2.4.1 Moon Island Beach Sub-group (M.I.B.)

The strata of the M.I.B. are far more persistent in their areal extent than the lower units of the Newcastle Coal Measures. Lateral variation in the composition of clastic sediments is limited mainly to comparatively minor grain size changes and consequently, correlation of units within the Sub-group is possible over a very wide area. The development of irregular but often thick lenses of coal within the thick conglomerate horizons does however cause local difficulty in the correlation of some coal seams. The geology of the individual units is discussed below.

The original subdivision of the M.I.B. by McKenzie (1962) has, in the light of the recent additional drilling information, been modified by Johnson (1969). Previous errors and inconsistencies were pointed out and it was concluded that many of the deficiencies resulted from the definition of the type section for the M.I.B. in outcrop areas where only a reduced section occurs. Attempts to extrapolate the established

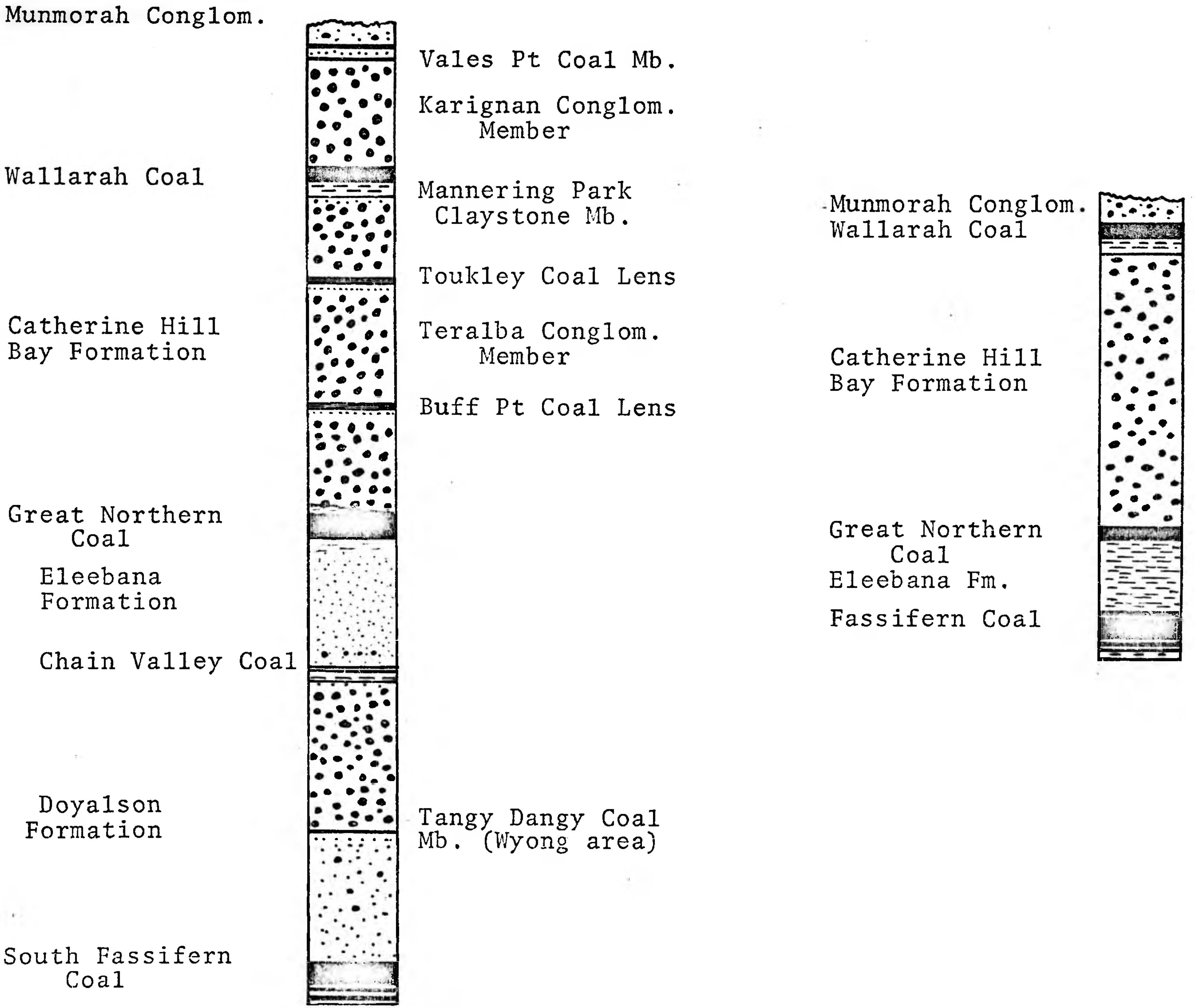

FIGURE 2.2b Maximum and minimum complete stratigraphic sections of the Moon Island Beach Sub-group

stratigraphy into the thicker non-outcropping areas failed.

Figure 2.2b shows the stratigraphy and the maximum and minimum complete sequences that exist while Figure 2.3 shows relevant geographic place names in the Newcastle area referred to in the text.

Cross-sections indicating the general stratigraphic relationships are given in Map 1.

2.4.2 Fassifern Coal (including South Fassifern Coal, Doyalson Formation and the Chain Valley Coal)

This forms the base of the M.I.B. and is a thick highly banded seam ranging in thickness from 10m to 2.5m. The structure of the South Fassifern Coal-Fassifern Coal is given in Figure 2.4. The thickness variations of the formations discussed in this section are shown in Figures 2.5, 2.6, 2.7. The lower part of the seam is irregularly developed and consists of interbedded claystone bands and thin coals. Frequently these coals are absent and as a consequence fairly rapid variations in total thickness of the coal occur over restricted areas. In the upper part of the seam some thick, widely developed plies of coal are present. While the seam section is variable, the definition of the base in particular being arbitrary, it is probably the most widespread coal formation in the M.I.B. The coal, like the other coals of the M.I.B. is of low-medium rank and has a high content of inorganic clastic material.

It outcrops near Fassifern, to the N.W. of the area under study, at Belmont (N.N.E.) and along the Swansea Peninsula (see

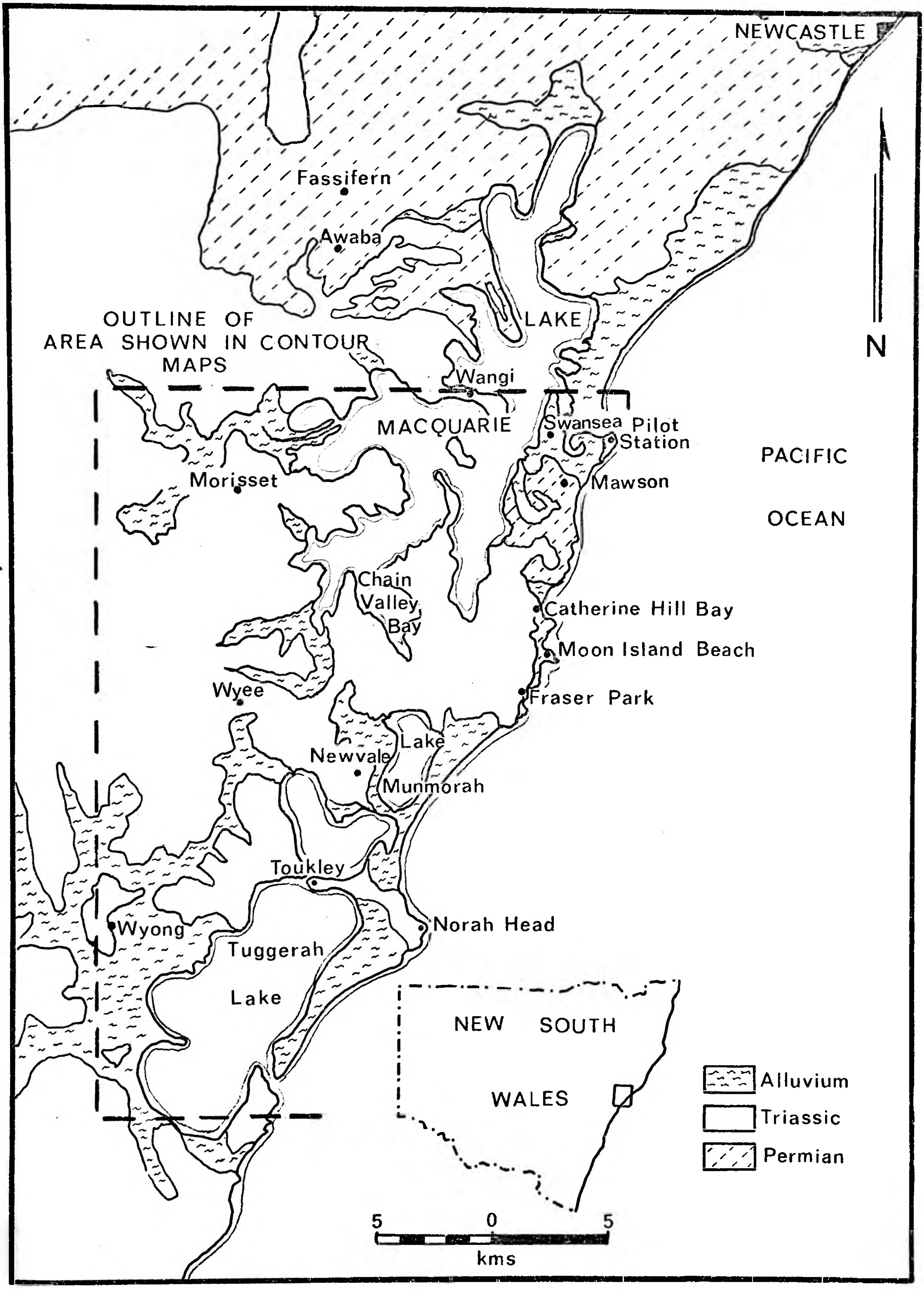

FIGURE 2.3 Locality map showing relevant place names

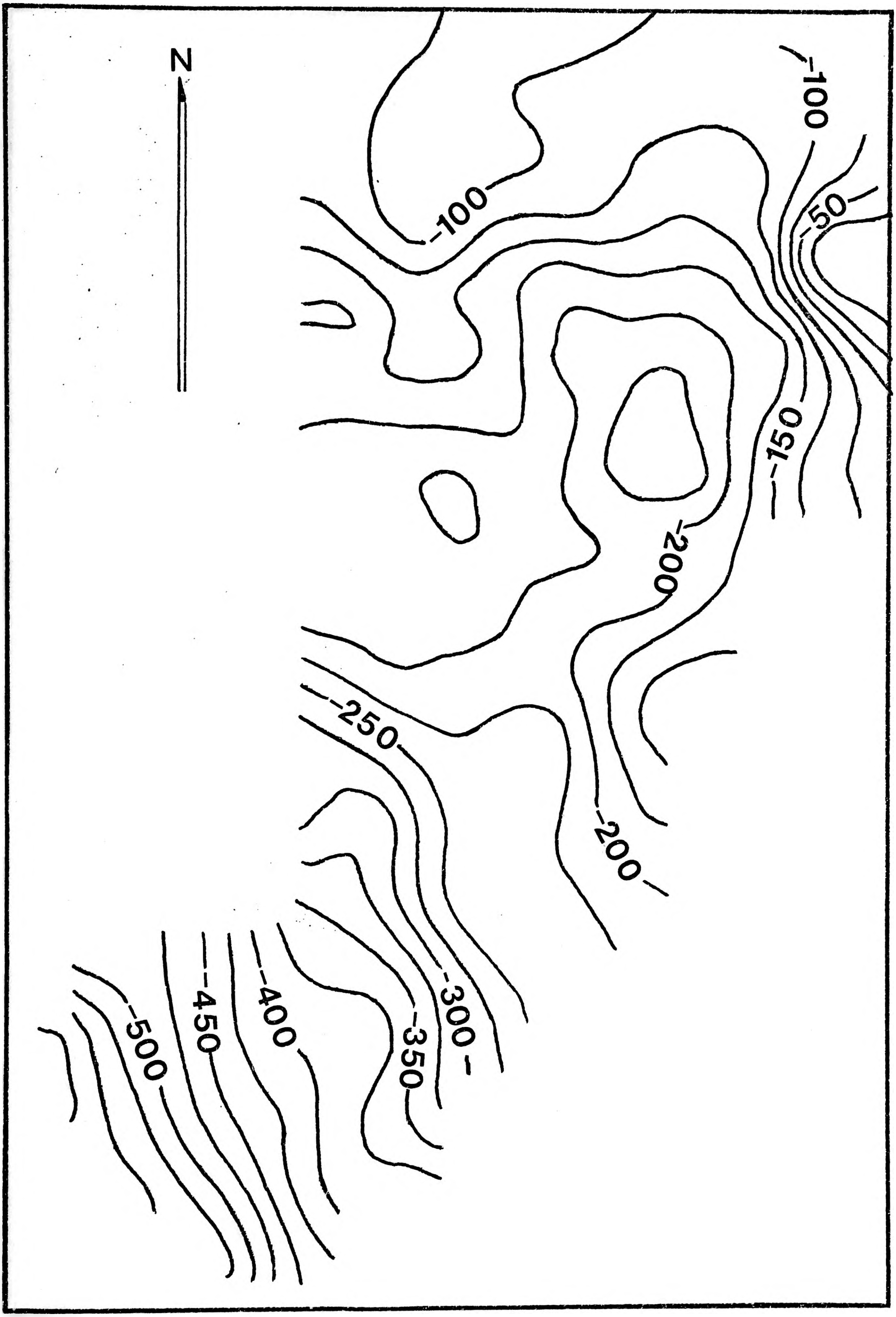

FIGURE 2.4 Structure of base of the South Fassifern Coal and the Fassifern Coal Contours refer to reduced level in metres and the scale is 1cm equals 1.5km for this and all other structure contour maps.
Contour interval :50 m.

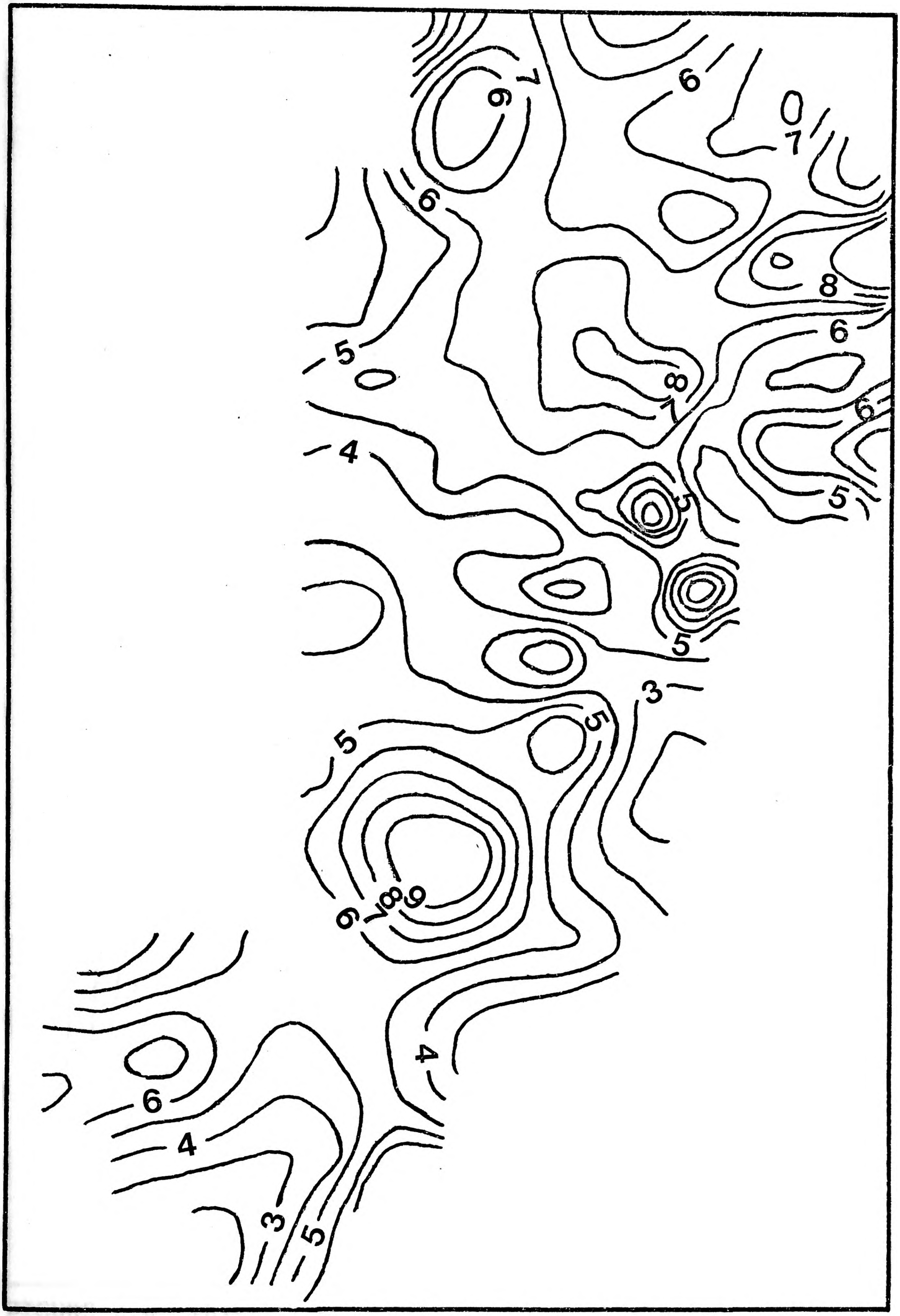

FIGURE 2.5 Thickness variations of the South Fassifern Coal and the Fassifern Coal. Contours refer to thickness in metres and the scale is 1cm equal 1.5 kms for this and all other structure contour maps. Contour interval: 1 m.

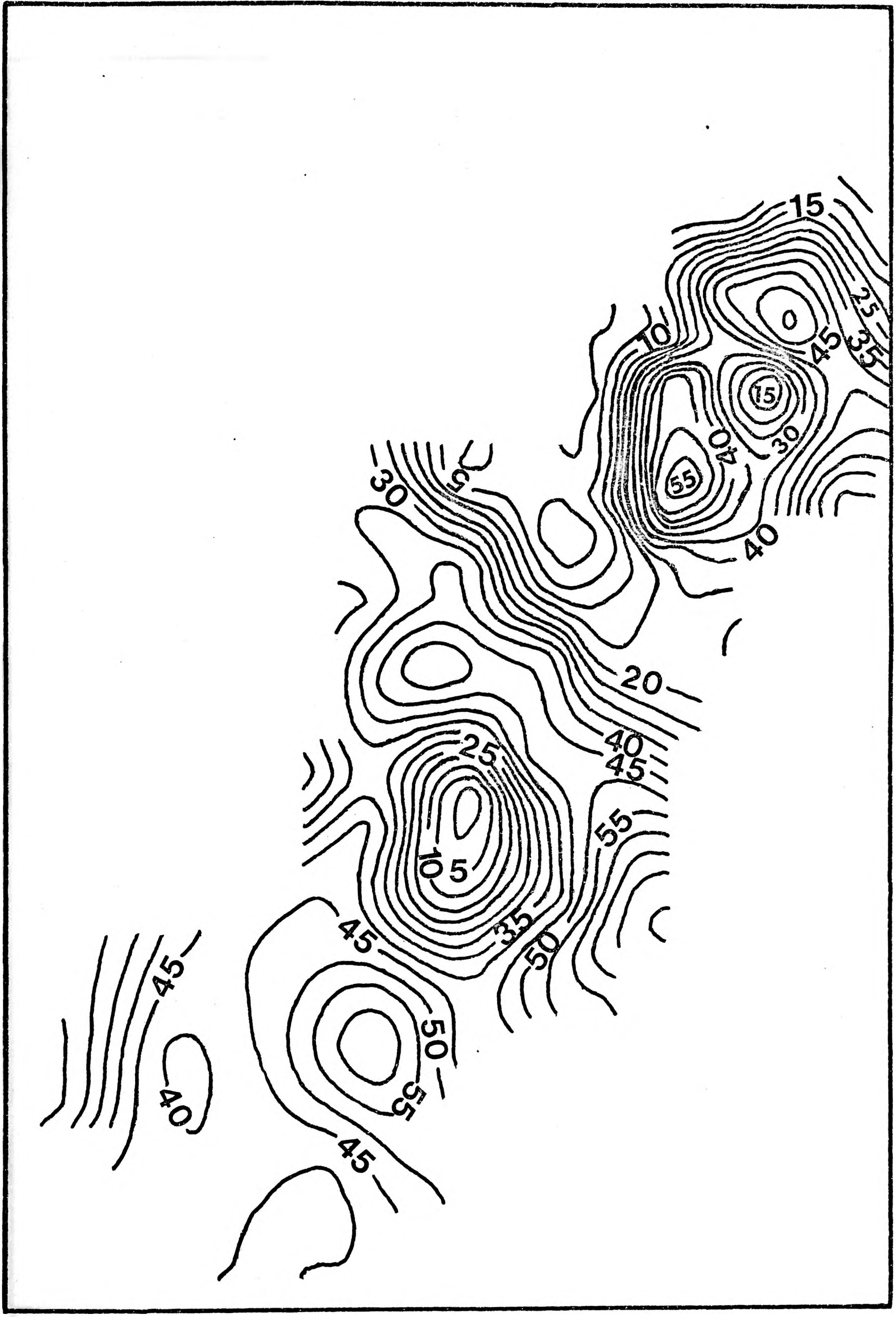

FIGURE 2.6 Thickness variations of the Doyalson Formation
Contour interval: 5m.

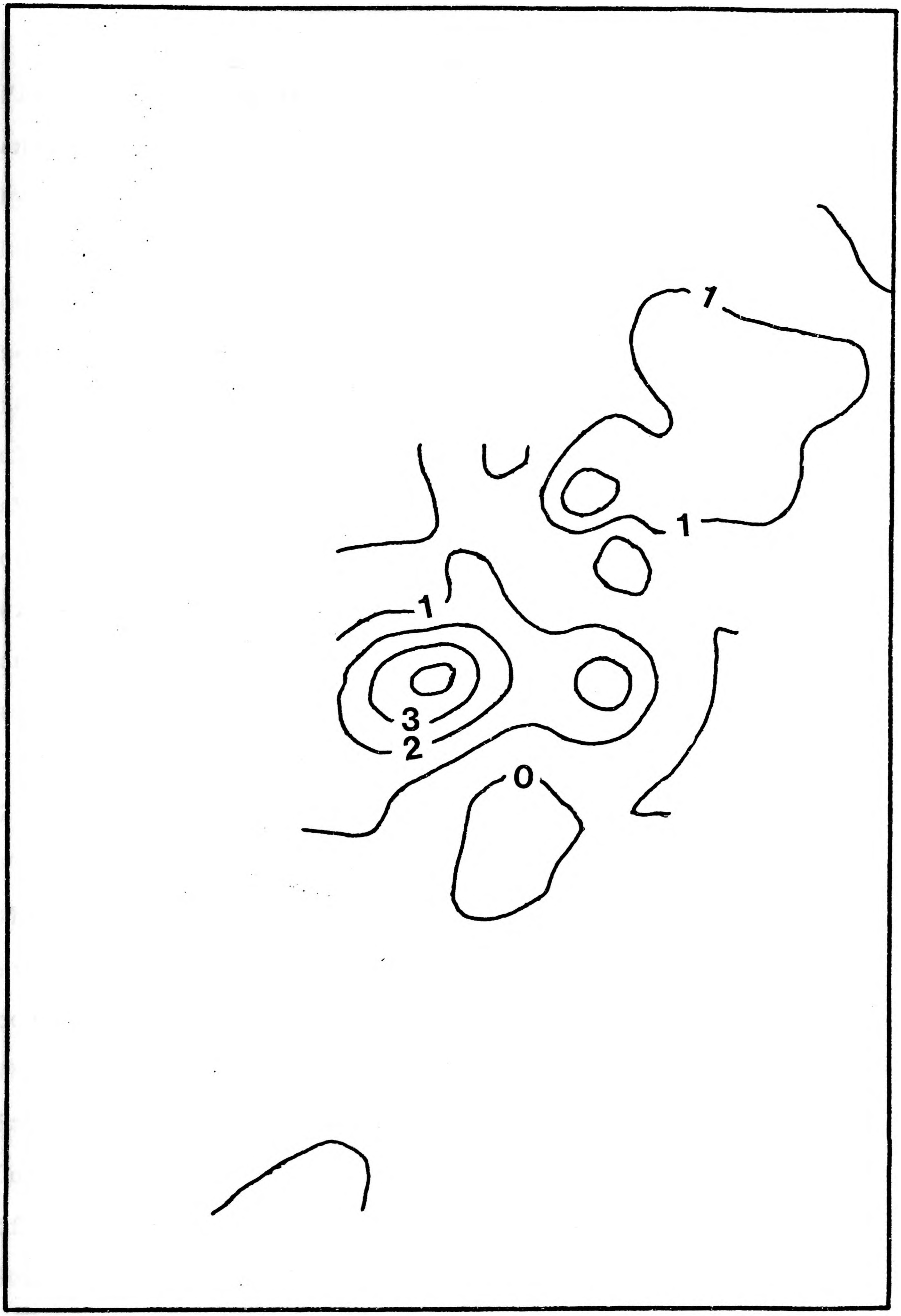

FIGURE 2.7 Thickness variations of the Chain Valley Coal
Contour interval: 1m.

Plate 2.3). From the type area at Fassifern it extends south and east over much of Lake Macquarie and is directly overlain by claystones and sandstones of the Eleebana Formation. However at the south end of Lake Macquarie a clastic wedge has developed, 'splitting' the upper part of the seam. The sediment is composed largely of claystone in the peripheral zone of the split sequence and, using borehole data, the claystone can be traced from a band less than 20 cm thick to about 5m thick over a distance of 2 km. The clastic wedge continues to thicken in towards its southerly trending axis with the appearance of coarse sandstone and conglomerate bands and in its thickest development is approximately 50m thick almost entirely composed of poorly sorted conglomerate (Fig. 2.8). This last stage may occur over a distance of less than 2 km in the maximum thickening direction across the axis of the wedge. In the areas where this clastic wedge has split the Fassifern Coal, certain difficulties arose in defining the stratigraphy of the intervening clastic unit and the overlying coal. This has been resolved by Johnson (1969) by subdividing the seam in these areas into three formations, the South Fassifern Coal, the Doyalson Formation, and the Chain Valley Coal. The South Fassifern Coal maintains the characteristics of the Fassifern Coal and in defining thickness variation, the South Fassifern Coal and the Fassifern Coal are considered as a continuous unit even though the top ply of the Fassifern Coal is not included in the region where both splits are separately

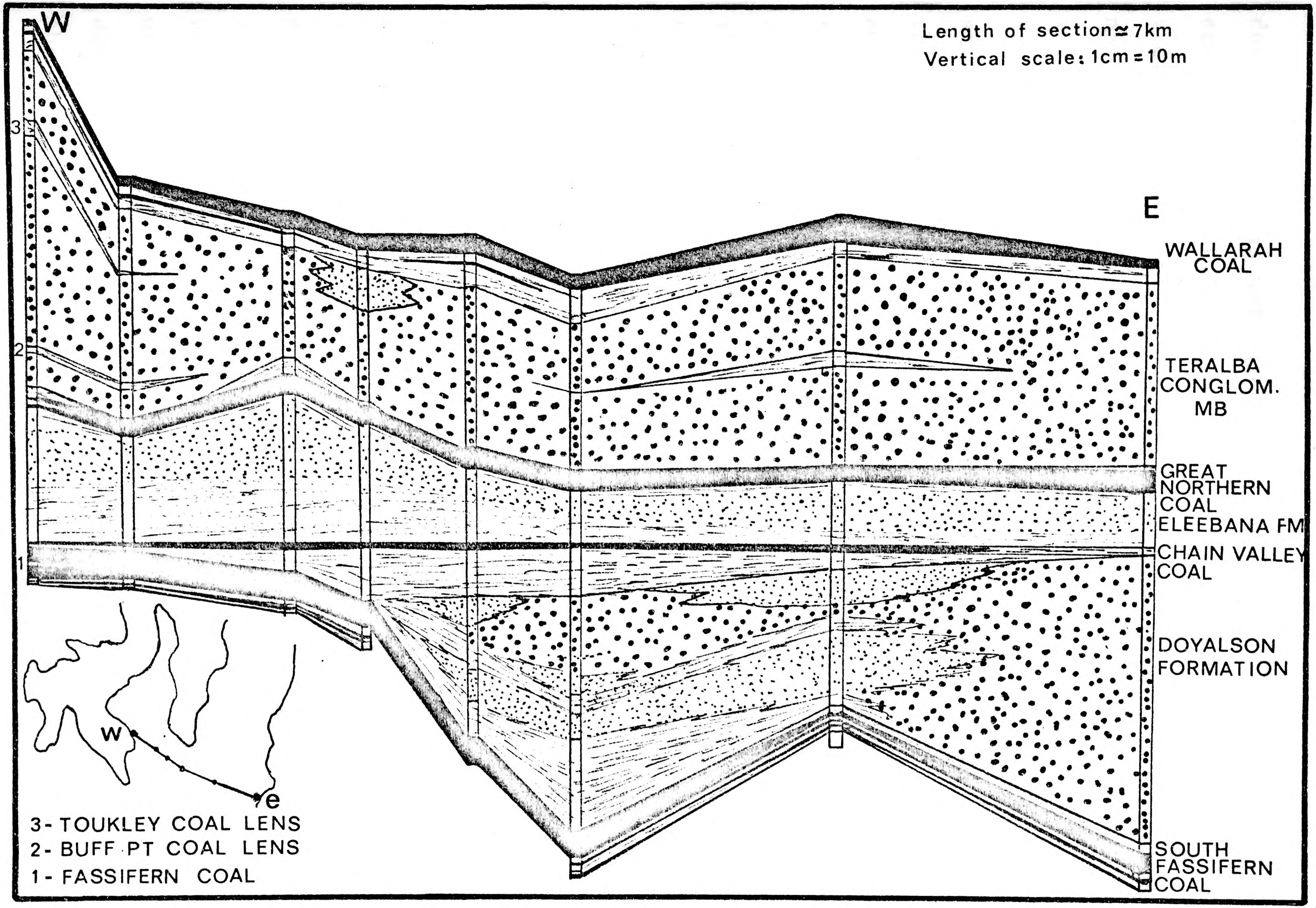

Fig. 2.8. Split in Fassifern Coal - south of Lake Macquarie

developed. It is not possible to define the Chain Valley Coal equivalent in the Fassifern Coal away from the immediate vicinity of the split. As a consequence the thickness variation maps of the Fassifern Coal may show certain inconsistencies in the area peripheral to splitting of the seam.

A test quarry, recently opened in the South Fassifern Coal at Swansea, has fortuitously been sited on the N.E. edge of the split. Plate 2.3 shows the Doyalson Formation (4m of claystone) gradually thickening to the south and overlain by the thin (1.5m) Chain Valley Coal. The unit overlying the coal is the Eleebana Formation (claystone and siltstone). South of this point the wedge widens and thickens and at Moon Island Beach south of Catherine Hill Bay (6 km south of the quarry), the Doyalson Formation is composed of dense, poorly sorted, cross-bedded conglomerate with pebbles up to 15 cms in diameter and of similar composition to the other Newcastle Coal Measure conglomerates. As can be seen from Figure 2.6 the wedge shows no major reduction in thickness to the south and it is still present in bores at Terrigal. South of Toukley, in the Wyong area, the proportion of conglomerate decreases and the lower part of the Doyalson Formation is sandstone. There is one isolated area to the north of Toukley where the Doyalson Formation has not developed. This is discussed in Chapter 5 under the results of trend-surface analysis. Restricted coal development occurs in the far south at the top of the sandstone: the Tangy Dangy Coal Member (Adrian, 1967). This unit has not

PLATE 2.3 Initiation of South Fassifern Coal-Chain Valley Coal Split, Mawson (looking south).

been studied here separately in detail as it only occurs in a few bores where there is limited areal control.

The Chain Valley Coal which ranges up to 3m in thickness (av. maximum 1.5m) and is usually highly banded with a high content mineral matter. It is of no economic importance under present economic conditions. This seam tends to vary rapidly in thickness and is normally underlain by thick carbonaceous shale and claystone belonging to the Doyalson Formation. Consistent definition of the unit is at times difficult. In the marginal zone between the thicker coarse Doyalson Formation and the thinner claystone equivalent the development of the Chain Valley Coal has not occurred. Across this inflexion region there is a thick sequence of carbonaceous claystones and fine sandstones (Fig. 2.8). However the top of the formation is distinct, with the overlying formation being relatively barren of carbonaceous remains.

2.4.3 Eleebana Formation

This unit overlies the Fassifern Coal in the northern part of the Macquarie Syncline and to the south overlies the Chain Valley Coal. In the area studied it contains one prominent member, the Awaba Claystone Member. Previously the Doyalson Fm. was incorrectly defined as the Bolton Point Conglomerate Mb. (McKenzie, 1962) and the Chain Valley Coal was included in the Eleebana Fm. The Bolton Point Conglomerate Mb. is a restricted conglomerate lens occurring to the north of the area studied

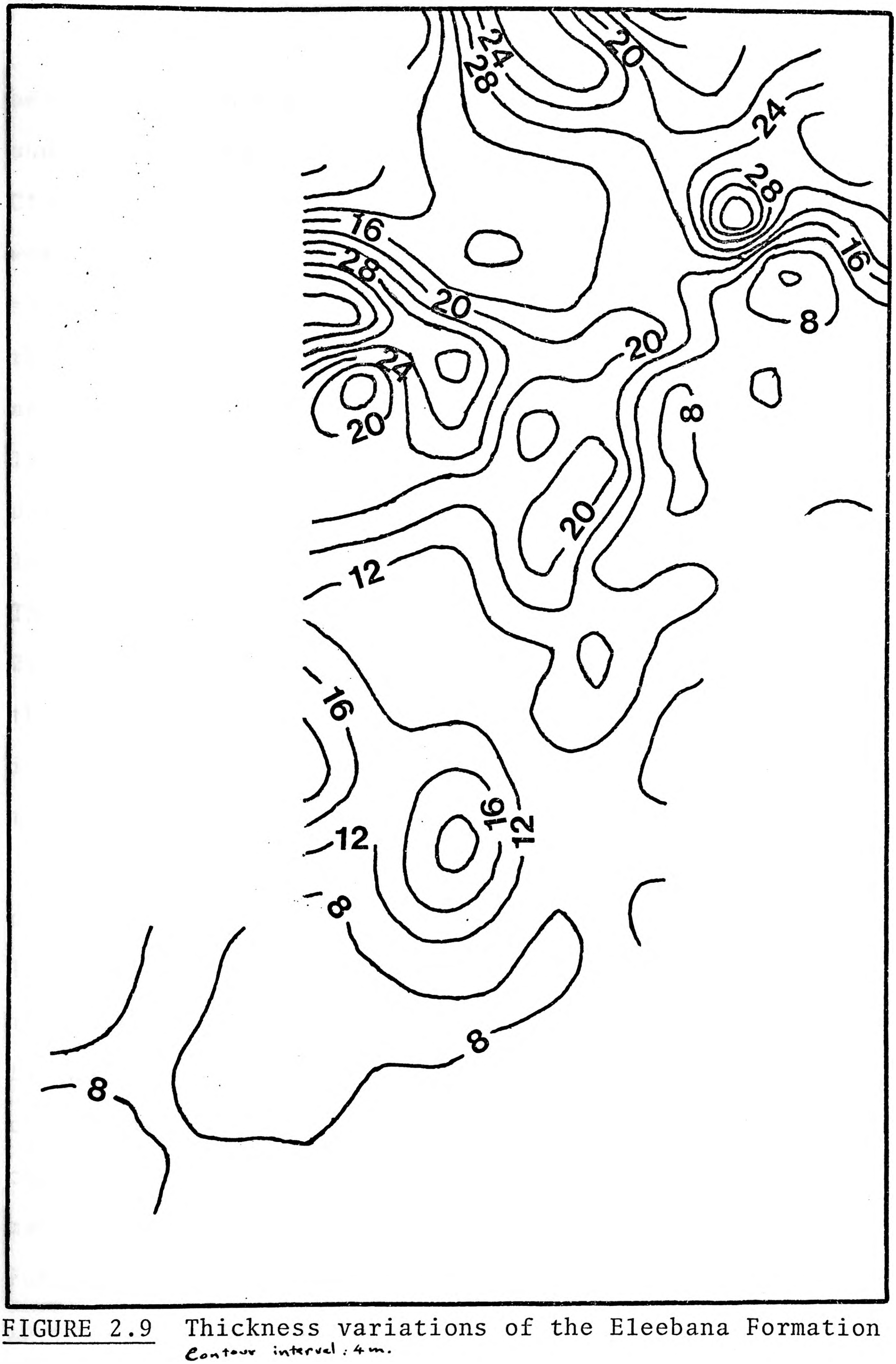

FIGURE 2.9 Thickness variations of the Eleebana Formation
Contour interval: 4 m.

below the Awaba Claystone Member within the Eleebana Formation and *above* the Fassifern Coal. The thickness of the Awaba Claystone Member in its outcropping type area to the north-west averages about 3m and varies only slightly. Figure 2.9 show the thickness variation of the Eleebana Formation. In this region it is a light buff-coloured claystone with brown and white micas forming an abundant minor mineral. Mixed-layered and kaolinitic clays predominate (Loughnan,1966a). This unit is frequently present as a pink cherty rock type either in whole or as fine irregular bands through the claystone. These cherty types are probably the result of diagenesis (see 2.3.5a). The name Awaba Claystone Mb. is somewhat redundant in this area as the other members have been deleted. However it is a convenient term to distinguish the claystone facies of the Eleebana Formation.

In the Lake Macquarie region to the south and southeast of the type area the Formation becomes sandy and even, in its lower part, slightly conglomeratic, with pebbles up to 3 cms in diameter. This coarse phase appears to be restricted to the west side of Lake Macquarie where it has caused local correlation difficulties. Over this area the presence of the coarse facies causes the section to thicken up to an average maximum of 20 to 25m. Biotite remains a prominent mineral. Further to the east in the Swansea area where the Formation is exposed (Plate 2.3) it is composed largely of claystone and siltstone. To the immediate south of Lake Macquarie the

Formation becomes sandy while in the extreme south in the Toukley-Wyong area the Formation thins to less than 10m and is a consistent dark grey-green mottled claystone. Some cherty zones are still present. In one small area near Lake Munmorah an isolated lens of conglomerate (5m thick, pebbles up to 10 cms) occurs at the base of the Formation and a thin carbonaceous sandstone is developed at the top of the lens; it is overlain by the usual Awaba Claystone Member facies.

Of special interest is the presence in the Eleebana Formation of vertical and *in situ* silicified fossil trees (*Dadoxylon*) which are found throughout the section. They are up to 0.5m in diameter and usually occur in localised groups. *In situ* fossil trees are common in the Newcastle Coal Measures and are especially prominent in the Eleebana Formation and the analcite-bearing cherty rocks immediately below the Pilot Seam. They are frequently seen in growth positions at the top of coal horizons (David, 1907) throughout the Newcastle Coal Measures.

2.4.4 Great Northern Coal

This seam is very persistent in its lateral extent and characteristically is almost free of discrete clastic bands. The coal is a dull, hard coal with low vitrinite content and low-medium rank. It has a high content of inorganic mineral matter. Its best economic development is in the extreme north of the Newcastle Coalfield at Pacific Colliery where it measures slightly under 8m thick. Over much of the area

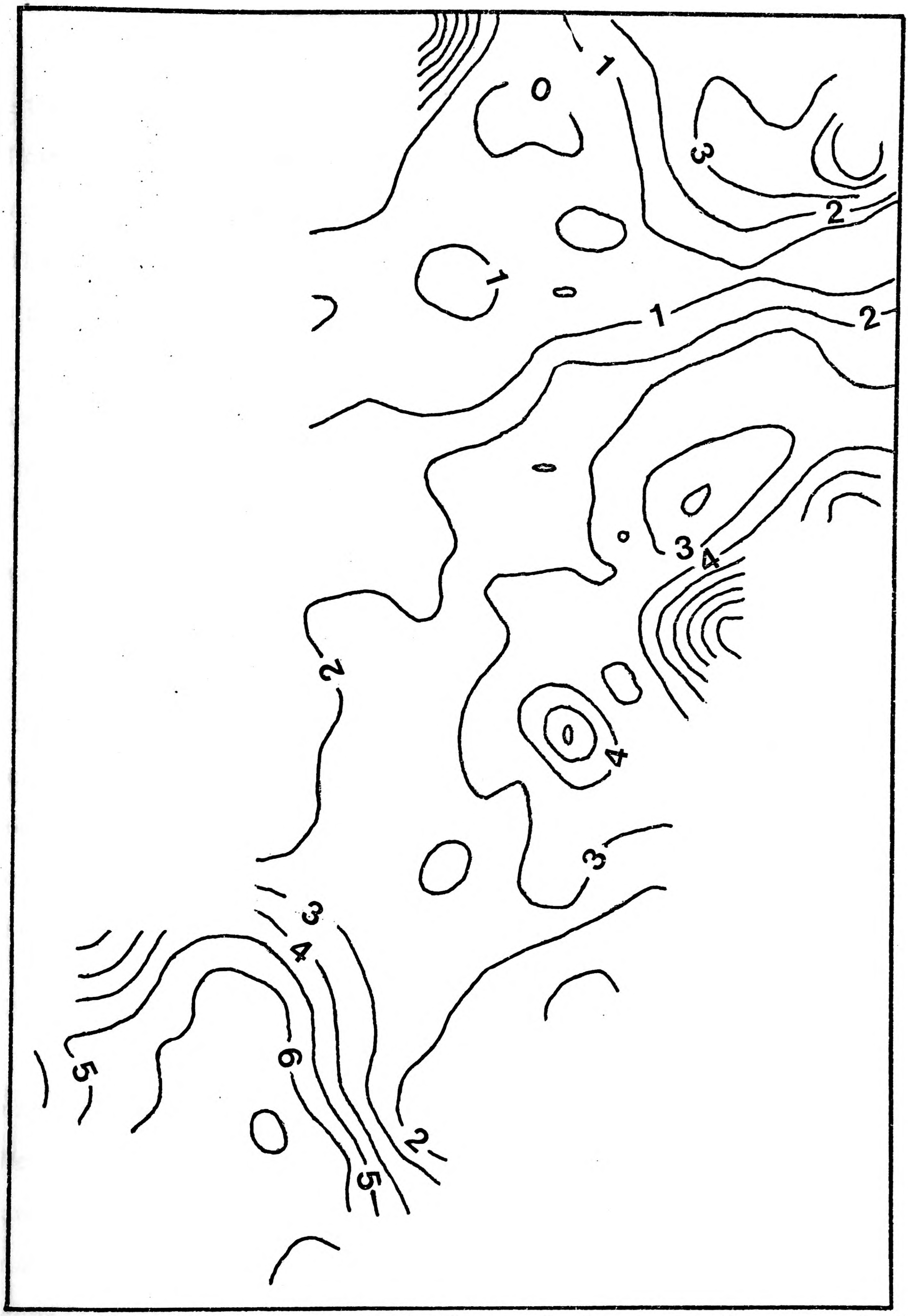

FIGURE 2.10 Thickness variations of the Great Northern Coal

Contour interval: 1m.

studied the seam is consistently between 2-3m thick (Fig.2.10). However in the Swansea area, across part of Lake Macquarie and on the west side of the Lake in the Morisset area the seam thickness is variable and it is absent in a few bores in these areas. Plate 2.4 shows the reduced seam at Swansea (0.5m thick) and Plate 2.5 a more typical full section at Catherine Hill Bay (3.5m). These areas of poor development may either be due to erosion of the seam by the overlying conglomerate or due to these areas being unfavourable for peat accumulation. A combination of both these effects is likely.

South of Lake Macquarie the seam is worked as a supply for the local power stations. The seam is up to 4m thick. In the Wyong area (far south) the seam thickens up to 7m with clastic bands fairly rare. The only splitting of the seam occurs in an area on the coast near Lake Munmorah where three claystone bands up to 1.5m separate coal plies in a total section of 9.2m.

2.4.5 Catherine Hill Bay Formation

This formation includes the most widespread conglomerate unit of the Newcastle Coal Measures, the Teralba Conglomerate Member. This conglomerate extends over an area of 400 sq. km and over much of this area exceeds 30m thick (Fig. 2.11). The maximum thickness is 70m, 2 kms north of Vales Point. It is composed of densely packed, poorly sorted pebbles up to 15 cms in diameter with an average maximum of 6 cms; the matrix is

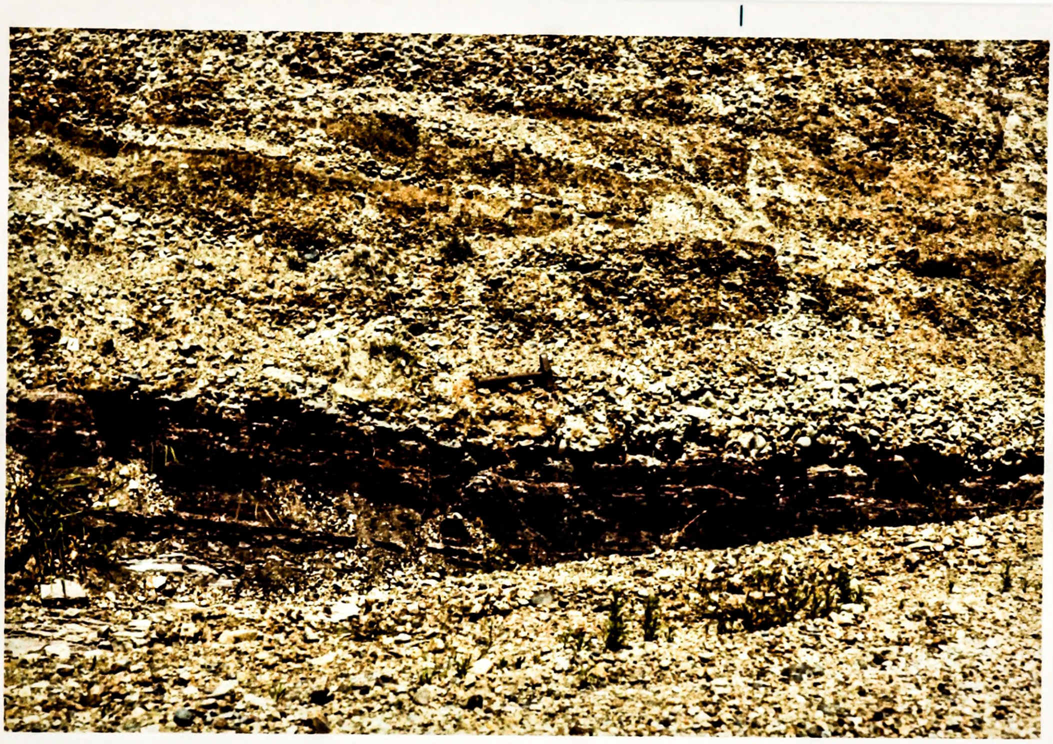

PLATE 2.4 Great Northern Coal at Swansea.

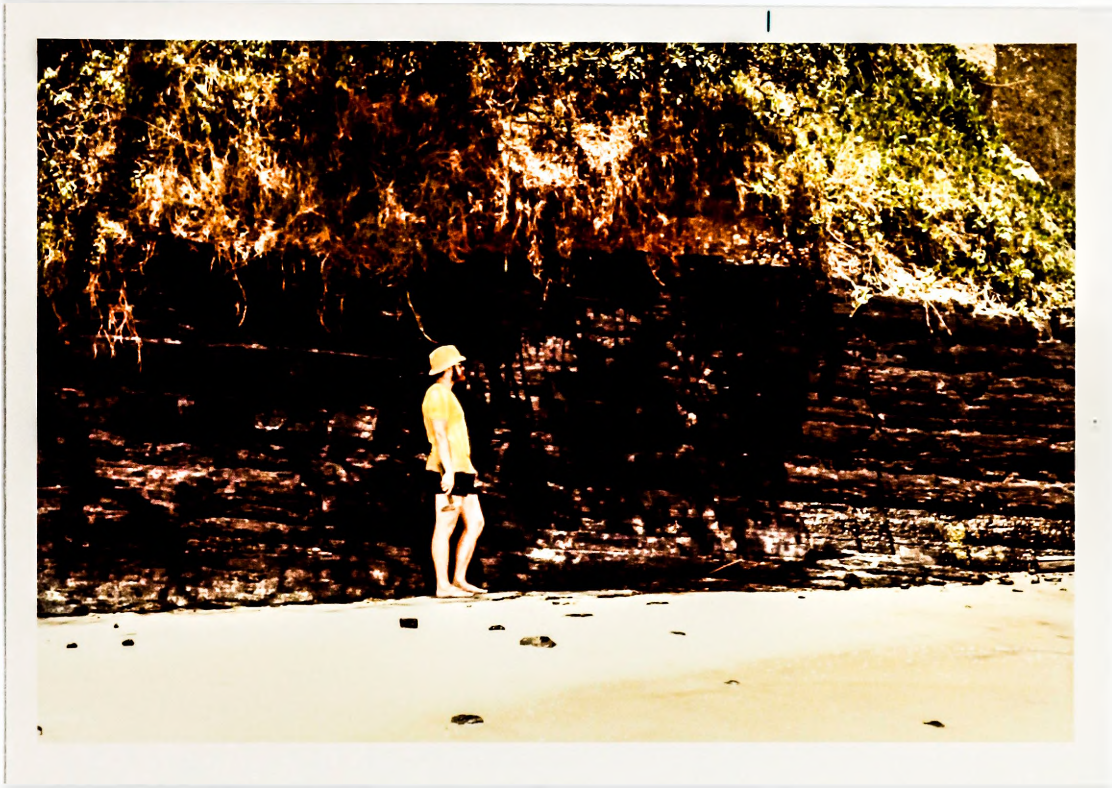

PLATE 2.5 Great Northern Coal at Catherine Hill Bay.

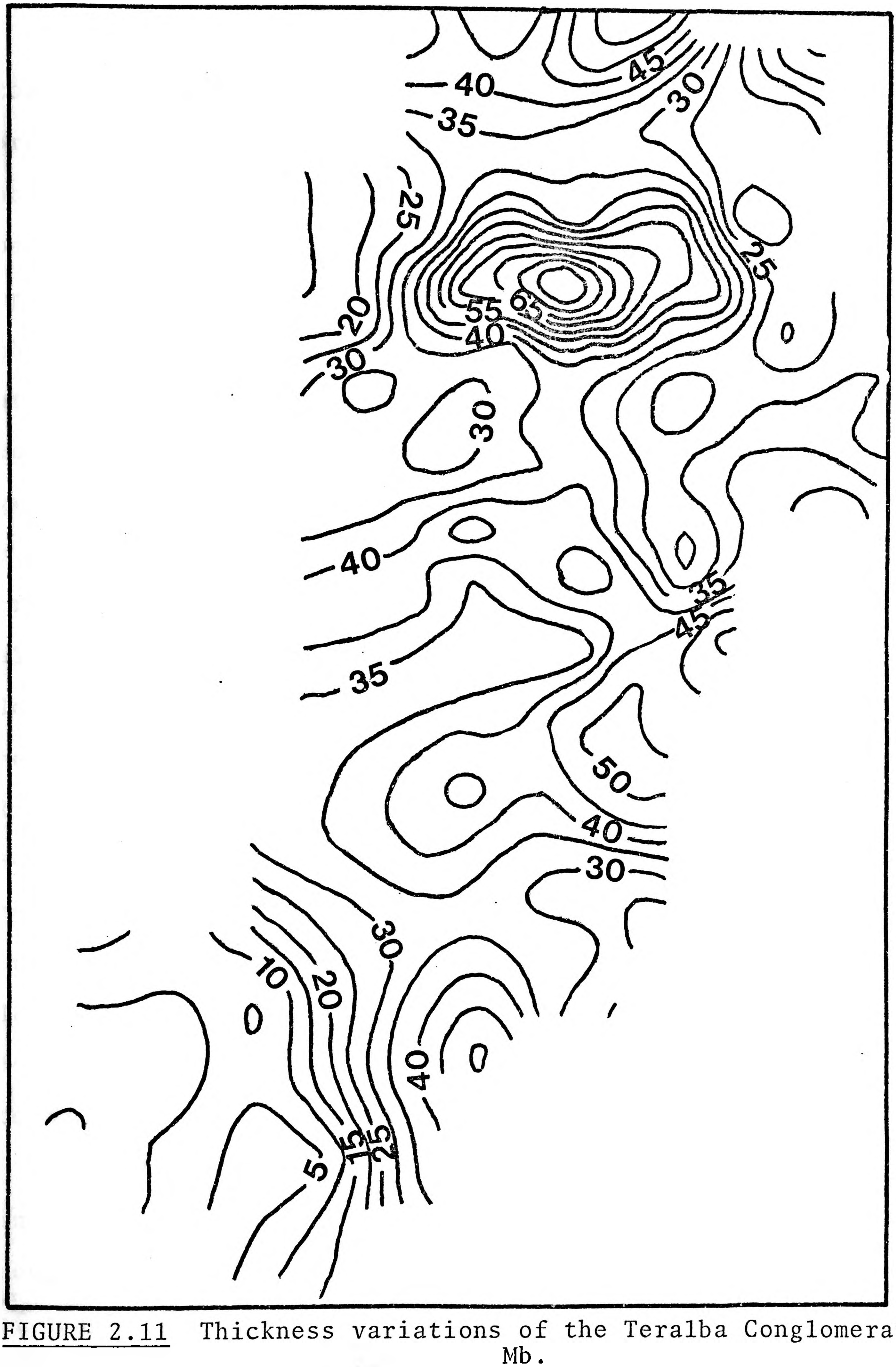

FIGURE 2.11 Thickness variations of the Teralba Conglomerate Mb.

Contour interval: 5m.

coarse sand, and clays probably derived from the *in situ* breakdown of the unstable volcanic detritus. Biotite is abundant in the matrix. The conglomerate is commonly cross-bedded with numerous thin sandy phases developed as fining-upwards graded beds and foresets (Plate 2.6). Plate 2.7 is a photomicrograph of a thin-section of one of these sandy phases at Moon Island Beach. Acid and basic volcanic detritus forms most of the grains, quartz constituting only about 20% of the grains. Fresh biotite is common and carbonate and quartz forms a weak cement. The Teralba Conglomerate Member outcrops prominently around the northern part of Lake Macquarie and along the coast south of Swansea. Within the conglomerate some laterally extensive sandstone horizons up to a few metres thick have been deposited in places and the section becomes an intercalated sequence of sandstone and conglomerate. The sandy sections are generally thinner than the adjacent conglomerate sections. This thinning may be due, in part, to differential subsidence of the massive, more dense conglomerate and the less dense sandstone-conglomerate interbedded sequence over a foundation of compacting peat as well as subsequent differential compaction of the formation.

Immediately south of Toukley there is a major facies change in the Teralba Conglomerate Mb. The composite fans of conglomerate pinch out and the section thins rapidly from 30m of conglomerate to 10m of sandstone (Fig.2.11). Farther south this interval has thinned to less than 4m of sandstone. The

PLATE 2.6 Fining-upwards sandstone phases in the Teralba Conglomerate Member, Catherine Hill Bay.

PLATE 2.7 Photomicrograph of sandstone from Teralba Conglomerate Mb. x15

effects of this rapid facies change can be seen in the overlying Wallarah Coal which thins and deteriorates in the region of this change.

At the base of the Catherine Hill Bay Formation and below the Teralba Conglomerate Mb a thin claystone horizon overlies the Great Northern Coal in some places. It may be up to 5m thick. From observations in colliery workings the lateral relationship with the conglomerate are erosional and the claystone is an erosional remnant. It is mainly confined to the Newvale-Lake Munmorah district although claystones sporadically overlie the Great Northern Coal over much of the area.

The Mannering Park Claystone Member forms the top of the Catherine Hill Bay Formation. The lower boundary with the Teralba Conglomerate Mb. is transitional and the section gradually fines upwards to the base of the overlying Wallarah Coal. The thickness of the Mannering Park Claystone Mb. is generally about 3-5m and has a maximum thickness of 6m east of Morisset (Fig. 2.12). It extends over all the area studied and is darker and more waxy in appearance than the other claystones.

Within the section of the Teralba Conglomerate Mb. two minor coals are developed. The lower unit, the Buff Point Coal Lens, is restricted to the Toukley-Munmorah area. The section is quite variable and may be up to 3m thick. It is composed of claystone bands and poor quality coal. The Toukley

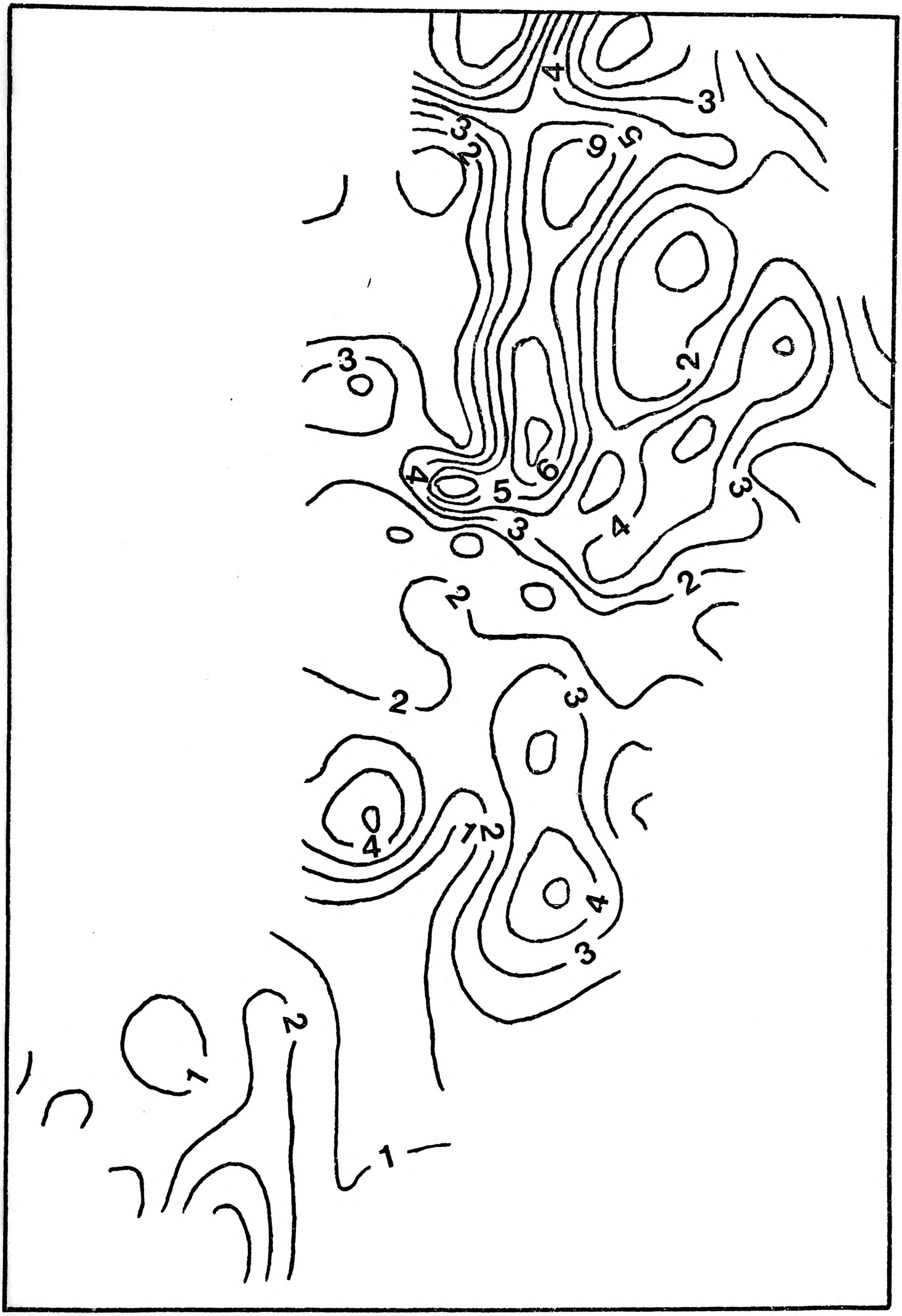

FIGURE 2.12 Thickness variations of the Mannering Park Claystone Mb.

Contour interval: 1m.

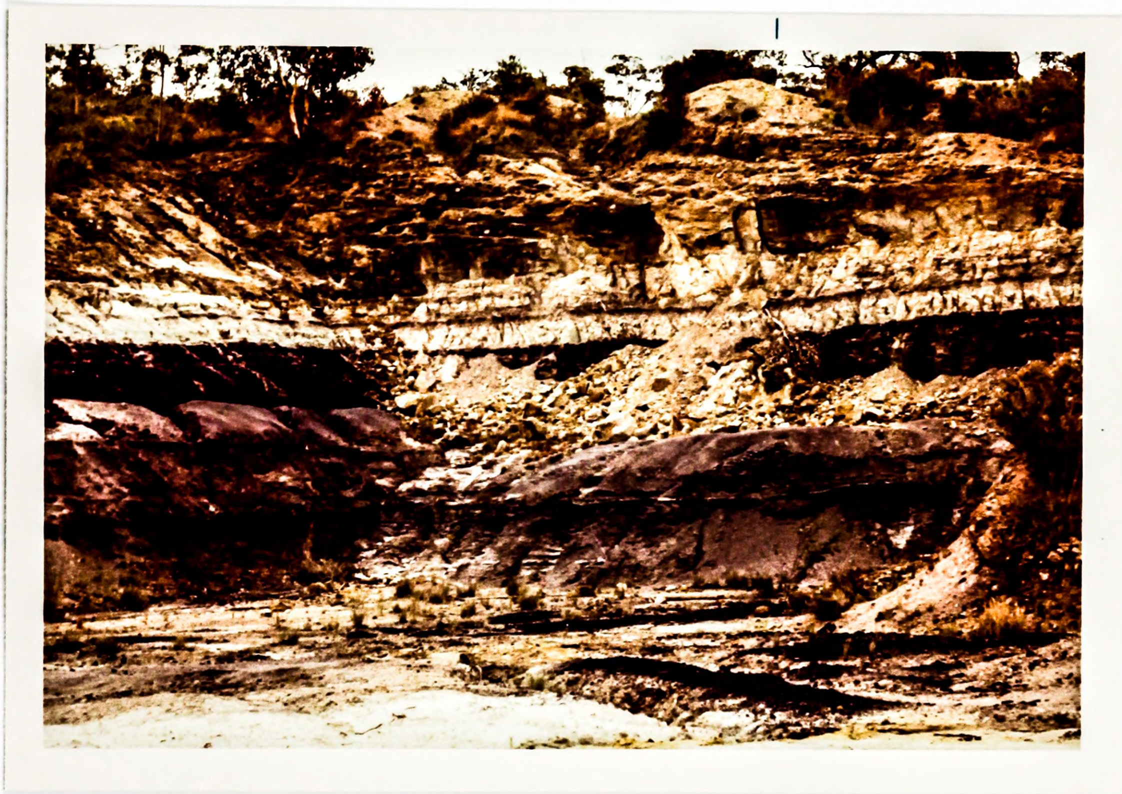

PLATE 2.8 Wallarah Coal at Catherine Hill Bay.

Coal Lens has a slightly greater extent and occurs from Toukley to the south of Lake Macquarie. It is slightly thicker than the Buff Point Coal but still consists of highly banded coal. Both units are generally underlain by thin sandstone horizons which in places extend into areas peripheral to the coal development. When both lenses are present they are usually separated by approximately 5m of conglomerate and sandstone.

2.4.6 Wallarah Coal (including Vales Point Coal Member)

This coal forms the top of the Newcastle Coal Measures in the type area definition (McKenzie, 1962). It is a hard, dull coal with few claystone bands but a high content of mineral matter. The thickness ranges from less than 0.5m at Wyong up to 6m in the Swansea area (Fig. 2.13). It is worked extensively in this latter area as a steaming coal. A carbonaceous claystone band which is present below the seam north of Catherine Hill Bay (Plate 2.8) becomes more carbonaceous to the north and in the area around Swansea two splits of coal are locally developed (Plate 2.9). Over much of Lake Macquarie a prominent clay band up to 1m thick occurs towards the base of the seam section. The Wallarah Coal thins to the northwest and to the south. In the southern area where the Teralba Conglomerate Mb. has pinched out, the thinning of the coal becomes extreme and in bores around Wyong, it is represented by only a few centimetres of coal. However it is very persistent and

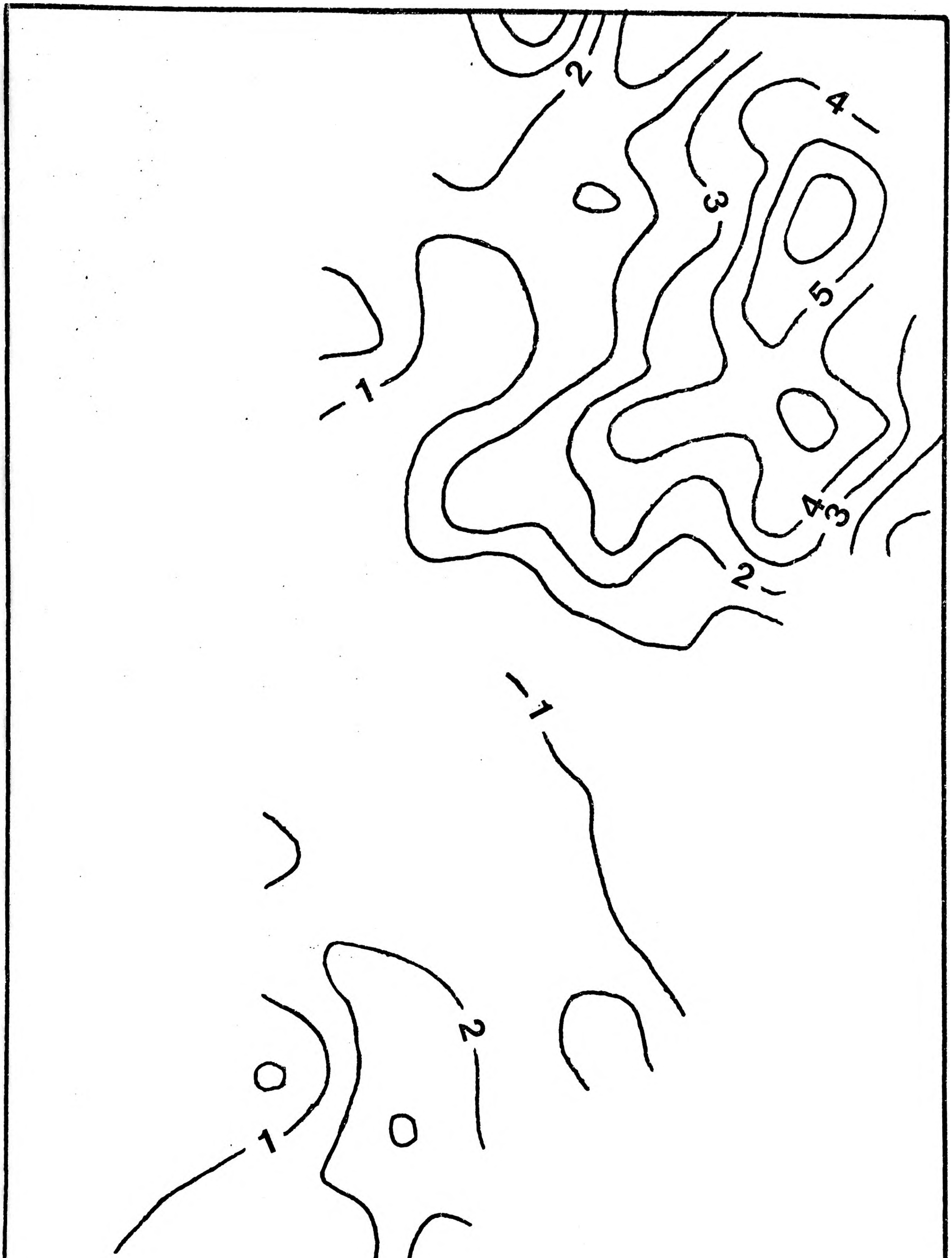

FIGURE 2.13 Thickness variations of the Wallarah Coal

Contour interval: 1m.

PLATE 2.9 Wallarah Coal at Mawson.

effectively extends over the entire area of study.

The Wallarah Coal is overlain by a range of rock types, some of which have affinities with the Newcastle Coal Measures and others which clearly belong to the conventionally-defined Triassic strata. Along the coast south of Catherine Hill Bay the seam is overlain by sandstones and conglomerates of the Munmorah Conglomerate, the lower formation of the Narrabeen Group. The contact is frequently erosional (Plates 2.10, 2.11). North towards Swansea shales and claystones with *Glossopteris* overlie the Wallarah Coal (Plate 2.8, 2.9). These in turn are overlain by Munmorah Conglomerate.

In the axial region of the Macquarie Syncline the Wallarah Coal is overlain by up to 25m of conglomerate (Karignan Conglomerate Mb), lithologically indistinguishable from the Teralba Conglomerate Mb. In this area a coal unit has developed on this conglomerate. This unit, the Vales Point Coal Mb. consists of two seams (generally less than 1m thick) separated by up to 10m of coarse, well-sorted white sandstone. The upper seam is overlain by conglomerates, sandstones and claystones of the Munmorah Conglomerate. Spore studies by Grebe (1970) of sediments immediately above and below the Vales Point Coal Mb. indicate that there is a floral change slightly above the Vales Point Coal Mb. Thus the Vales Point Coal Mb. and Karignan Conglomerate Mb. are of Newcastle Coal Measures and also of Permian age. It is not possible, however, to correlate the Vales Point Coal Mb. or the Karignan Conglomerate Mb. with the

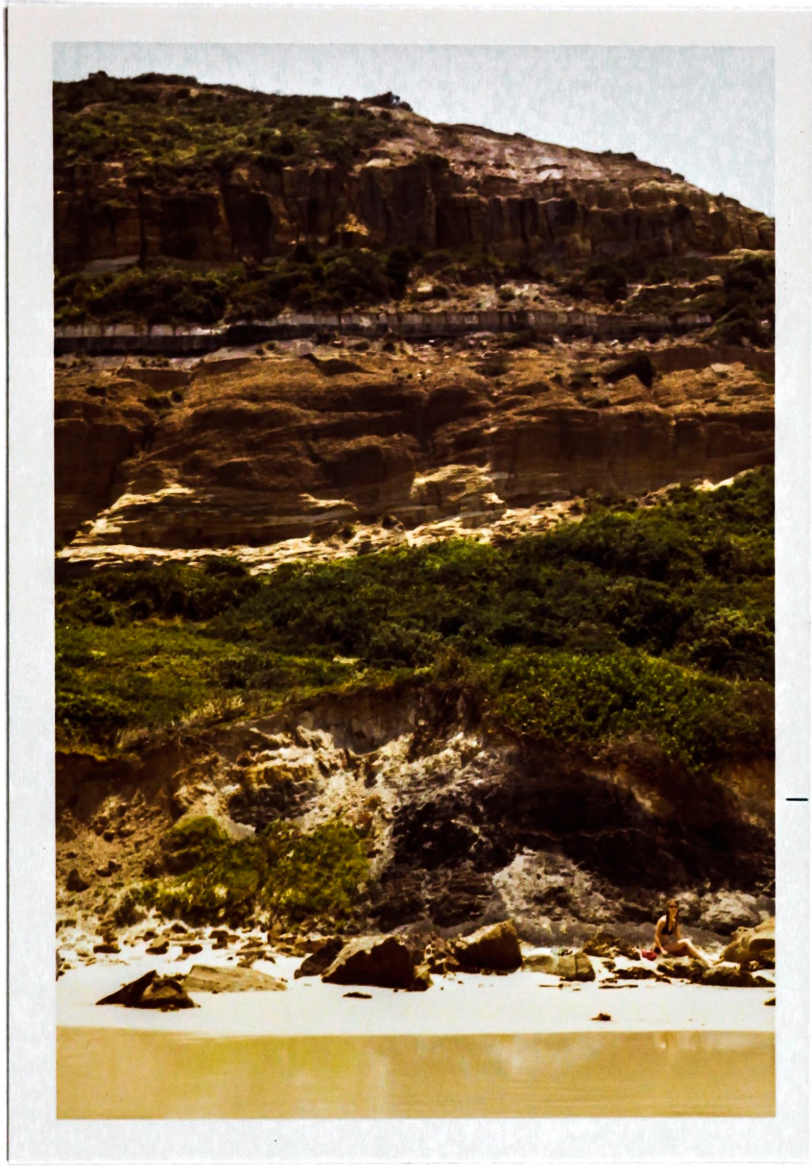

PLATE 2.10 Cliff section of Great Northern Coal (base), Teralba Conglomerate Mb, Wallarah Coal and Munmorah Conglomerate at Moon Island Beach.

coastal type section (Plate 2.10). The generally accepted stratigraphy based on the type section of David (1907) defined the top of the Wallarah Coal as the top of the Newcastle Coal Measures and overlying strata were defined as Triassic. The workers who first recorded the new drilling data followed this conventional boundary and considered the Vales Point Coal Mb. and the Karignan Conglomerate Mb. as members within the Munmorah Conglomerate. Although this is obviously erroneous, difficulties in defining the top of the Newcastle Coal Measures in areas where the Vales Point Coal Mb. is absent or where the Wallarah Coal is not overlain by sediments belonging to the typical Munmorah Conglomerate facies, have resulted in this stratigraphy being retained.

To the south the Vales Point Coal Mb. gradually pinches out and the underlying conglomerates and sandstones merge with the Munmorah Conglomerate. Interestingly this occurs in the same general region as the Teralba Conglomerate Mb. pinches out and the Wallarah Coal begins to thin. These two units above the Wallarah Coal are included in the subsequent analysis for completeness as they represent the last episode of coal measure deposition in this area.

In a new exposure in the open cut mine in the Wallarah Coal at Swansea a dark grey-green channel sand (up to 0.5m thick) has washed out part of the claystone overlying the seam (see Plate 2.12). The dark green sand is overlain by 3m of light coloured sandstone with a slight greenish tinge. This

PLATE 2.11 Erosional contact of Munmorah Conglomerate and Wallarah Coal, Fraser Park.

is in turn overlain by quartzose sandstones typical of the Munmorah Conglomerate. The dark channel sand is obviously a remnant of the Karignan Conglomerate Mb. and inspection of thin sections cut from this sand indicate that it has strong Newcastle Coal Measures affinities (abundance of rock fragments and a paucity of quartz). The overlying sand is a mixture of reworked Newcastle-type sandstone (i.e. Karignan Conglomerate Mb.) and quartzose Triassic sediment. It is probably this gradational break that makes this boundary so difficult to identify in bore core. However in this one locality the boundary between the Newcastle Coal Measures and the Munmorah Conglomerate could be satisfactorily placed at the top of the thin dark grey-green sandstone.

PLATE 2.12 Remnant of Karignan Conglomerate Mb (dark green sandstone) overlying Wallarah Coal and underlying light-coloured Munmorah Conglomerate sandstone, Mawson.

CHAPTER 3

METHODS OF ANALYSIS

3.1 INTRODUCTION

The first step in any study of stratigraphic data using mathematical methods is the development of a reliable correlation of the units in the given sedimentary sequence. This knowledge of the geometrical relationships of rock units is used as a basis for subsequent analysis. The numerical data for this analysis can then be extracted from the bore logs and collated into a usable form to be processed and analysed by the desired techniques.

Mathematical methods generally entail a considerable amount of calculation effort and high-speed computers are used to facilitate the analysis. This also enables the analysis of a large number of variables with a minimum of work once the computer programs and data are set up into a production system. An important extension to the analytical methods is the presentation of results in contour map form and the cross-correlation of given variables to determine their relationships.

The separate phases in the analysis, from the raw data to the methods and interpretation, are outlined below.

3.2 DATA COLLECTION AND ORGANISATION

The raw data for this study consists of the bore logs of approximately two hundred surveyed, fully-cored diamond drill-holes sunk in the area of interest over the past seventy years. Only a few, however, are more than fifteen years old. They are not regularly spaced and are concentrated around colliery holdings in the area. The bores have been logged by a number of different geologists from various government organisations and companies, and this has lead to an absence of consistency in coal seam definition and description of the lithologies. These deficiencies are partly met by the author's familiarity with the logging techniques of most of the geologists involved and the lithologies encountered in the bores.

Some workers defined the geological thickness of the coal seams from the base of the lowest coal ply to the top of the uppermost coal ply; others included shales and claystones which contained minor plant remains and underlie most coal formations as part of the defined coal seam. In this study the coal seams were defined such that carbonaceous shale, but not grey shale with carbonaceous remains, was included in the seams. Carbonaceous shales (i.e. black or brown shales containing an abundance of organic material) were usually only present as thin bands (<10 cms) at the bases of some seams.

Also although each geologist had correlated the bores logged by themselves to their own satisfaction no correlation across the whole of the region had been carried out. This constituted the first phase of the study. The earlier piece-meal approach resulted in groups of bores logged by certain workers being totally miscorrelated.

Each written log was drafted into a graphic log at a scale of 1" = 20 feet, the bore measurements all being in non-metric units. As much information as possible was placed on these logs to minimise later reference to written logs for checking. Detailed correlation of the units within the sequence was carried out using a triangular correlation system instead of section lines. All the bore-hole location points are broken into the minimum number of near-equilateral triangles and the three bores in each triangle are correlated first with each other and then the three adjacent triangles. Hence polygons of correlated bores are built up. The area of maximum section development (Chain Valley Bay) was selected as a starting region and the correlation was gradually extended from here into the peripheral outcrop areas (and type sections) where a reduced section sometimes occurs. In this way the correlation is strictly controlled. Actual nomenclature at this stage is not important as the essential processes are matching sequences and pairing individual lithosomes. As mentioned in Section 2.4 certain inconsistencies did arise between the type-sections and the thicker sub-surface successions; where necessary the stratigraphy was modified accordingly.

When the bore sections were satisfactorily correlated, the level data of the base of sixteen consecutive units were extracted from the written log and transferred to specially coded recording sheets with a particular field on the coding sheet for each stratigraphic unit. Other data collected at this stage were the bore name, grid location (as easting or northing), the collar R.L., and an optional alphanumeric comment on the bore section (i.e., any peculiarities in the section, or local uncertainty as to the correlation of a unit). Absences of any unit, the presence of intrusive igneous material (usually dykes), or evidence of faulting were also noted.

Data from the coding sheets were then punched onto cards. A program to organise this data, calculate thicknesses and display a stratigraphic log of each bore was written; a sample of the output is given in Fig. 3.1. This regenerated log was used for the checking of recording and punching errors. When these errors were corrected a final regenerated bore log set was produced and the card data transferred to magnetic tape. As a final check on the data low degree trend-surfaces were calculated and the residual values inspected for isolated 'wild' values which were then rechecked against the graphic log. From this file individual data decks for each unit containing bore name, grid co-ordinates, and reduced level and thickness for each bore were generated as the input for the trend-surface analysis. In this last stage the thickness and level measurements were transformed to metric units. Also at

BORE NAME NEWVALE DDH 27
BORE LOCATION 4579. EAST.
8973. WEST.

COLLAR
LEVEL = 2.31 FEET ASI

STRATIGRAPHIC UNIT	REDUCED LEVEL	THICKNESS	DEPTH
VALES POINT COAL MEMBER	-394.25	44.46	396.56
KARIGNAN CONGLOMERATE MEMBER	-444.44	50.19	446.75
WALLARAH COAL	-449.15	4.71	451.46
MANNERING PARK CLAYSTONE MB.	-458.86	9.71	461.17
TOUKLEY COAL LENS	-495.95	1.37	498.26
BUFF POINT COAL LENS	UNIT IS NOT PRESENT		
TERALBA CONGLOMERATE MEMBER	-583.19	124.33	585.50
CLAYSTONE,ROOF GT NORTHERN	UNIT IS NOT PRESENT		
GREAT NORTHERN COAL	-595.29	12.10	597.60
AWABA CLAYSTONE MB.	-635.28	39.99	637.59
CHAIN VALLEY COAL	-635.43	0.15	637.74
CLAYSTONE,BASE CHAIN VALLEY	-646.87	11.44	649.18
DOYALSON FORMATION	-676.15	40.72	678.46
(STH) FASSIFERN COAL	-687.34	11.19	689.65

TOTAL DEPTH IS 745.00 FEET

REMARKS: THIN SHALE ABOVE TOUKLEY: BORE TERMINATED IN MIDDLE
OF (STH) FASSIFERN

FIGURE 3.1 Sample of output from program to collate bore-hole data.

this stage a number of bore-hole points was removed from the final file in the manner outlined below.

3.2.1 Selection and Spacing of Data Points

An inspection of Fig. 3.2 shows that drilling activity has been concentrated in certain localities. Although data points need not be regularly spaced for regression analysis they should be more or less equally distributed geographically (Harbaugh and Merriam, 1968). Clusters of data points can cause undue influence on the trend-surface function causing it to pass closer to groups of closely spaced points than to an isolated point under certain conditions of data distribution (e.g. Parsley, 1971). In a regional study of areal variation each unit of area is as geologically significant as any other and there should be an equal chance for each unit of area to be included in the sample population.

Various measures are available to control the effects of clustering of data points on the regression coefficients. These usually involved superimposing a grid system over the control area and reducing the effective number of data points per grid cell to a minimum concentration. This may be done by a random rejection process, or by inversely weighting the data in proportion to the number of data points, or to the square root of the number of data points if less severe weighting is desired. Removal of data points causes a decrease in the degrees of freedom in the data and may lower the degree of

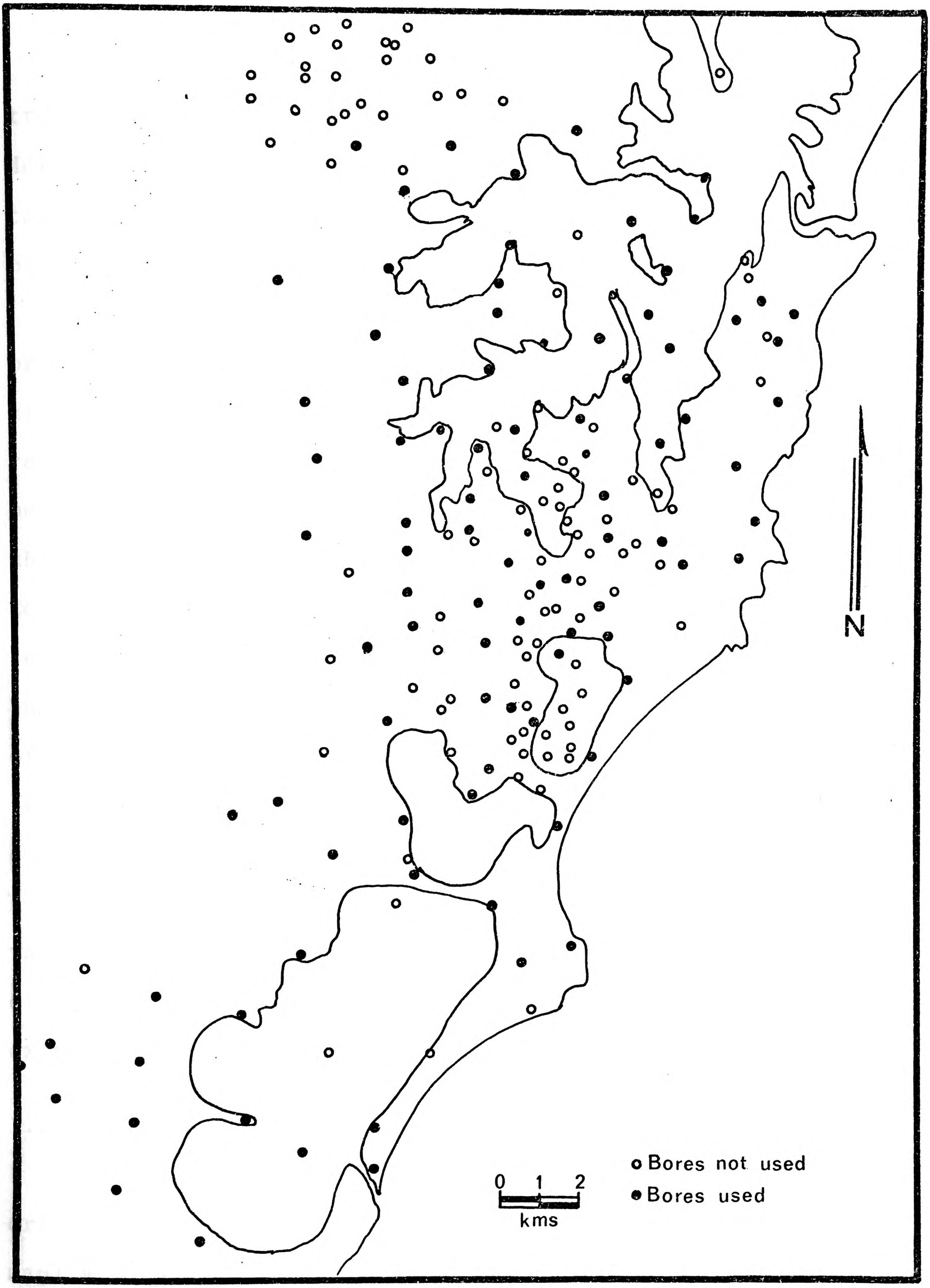

FIGURE 3.2 Map of bores available and those used in this study

trend function which may be usefully calculated. The contour detail of the residual map suffers because of the fewer control points; however, the overall accuracy and reliability of the residual map is enhanced.

With the bores being used in this study such rejection procedures were not required; while there was extreme clustering with the data points on the top two seams there was relatively little clustering for the bores which actually penetrated a full section of the M.I.B. Firstly all bores in the clustered areas which did not penetrate both the Wallarah Coal and the Fassifern or South Fassifern Coal were rejected. In the outcrop areas of the M.I.B. the bores which intersected only the lower part of the M.I.B. section were deleted. Removal of a few closely-spaced points which remained was carried out to achieve an even distribution. The final distribution of control points used is given in Fig. 3.2. However all bore holes are not common to each unit. Except for slight variations around the edges of the area covered,the data point distribution in Fig. 3.2 is applicable to all units which extend over the entire area

3.2.2 Errors in Data

Minor errors in the accuracy of the bore location are not critical since all grid co-ordinates (taken from a 1:63,360 base map) are rounded to the nearest 100 yards. Non-random errors in collar level may affect the structure residual maps but will be of less importance in the trend-surface maps. The preliminary trend-surface residual maps were used to check for gross errors in collar level which should show up as spurious, isolated inflexions in the contours. Only one bore was rejected as being suspect, while a slight deviation in the contour pattern in the structure residual maps occurred around two bores sunk on adjacent sides of a fault in the Vales Point area.

Unrealistic thickness variations caused by localised "washouts" in the seam or inaccurate thickness measurements due to core losses were considered unacceptable and likely to influence subsequent interpretation. The main control on this source of error was from the remarks and descriptions afforded by the written lithological log of the seam. A few intersections were rejected, mainly on the basis of known core-losses due to the termination of coring runs in the middle of the seam section. Consequently the number of data points for the thickness variables is often slightly less than for the corresponding structure data set.

3.3 TREND-SURFACE ANALYSIS

The background and general approach of trend-surface analysis has been outlined in Section 1.4.2. The methods of carrying out the analysis and evaluation of the results are described in detail below.

3.3.1 Matrix Inversion Method

Trend-surface analysis is the application of the general linear model for the regression analysis of areally distributed variables and involves the fitting of continuous mathematical functions which approximate the distribution of the observed values of the variable. The regression function is usually based on the least-squares criteria. The method of calculation of regression coefficients with irregularly-spaced control points is fully described by Krumbein & Graybill (1965)

Briefly the general linear model may be written as

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i X_i + e \qquad \ldots.(3.1)$$

where the β_i's are unknown parameters and the variance of Y is σ^2, and where σ^2 does not depend on the X_i nor the β_i; e is an unobservable random variable such that the expected value of e is zero, with variance, σ^2

$$E(e) = 0, \quad var(e) = \sigma^2 \qquad \ldots.(3.2)$$

For example a third degree polynomial with full cross-product terms for two independent variables X_1 and X_2 becomes

$$Y = \beta_o+\beta_1X_1+\beta_2X_2+\beta_3X_1^2+\beta_4X_1X_2+\beta_5X_2^2+\beta_6X_1^3+\beta_7X_1^2X_2+\beta_8X_1X_2^2+\beta_9X_2^3+e \qquad \ldots.(3.3)$$

For a given set of observed X_i, Y_i where the number of sets of data values, n, is greater than or equal to the number of unknown β_i, k. i.e. $n \geqslant k$

then

$$\left.\begin{aligned} Y_1 &= \beta_o + \sum_{i=1}^{k} \beta_i X_{1k} + e_1 \\ Y_2 &= \beta_o + \sum_{i=1}^{k} \beta_i X_{2k} + e_2 \\ &\cdots\cdots\cdots\cdots\cdots\cdots \\ Y_n &= \beta_o + \sum_{i=1}^{k} \beta_i X_{nk} + e_n \end{aligned}\right\} \qquad \ldots.(3.4)$$

In order to determine the unknown coefficient set β the method of least-squares is used.

The least-squares estimators of the β_i are obtained by minimizing the sum of squares of errors $\sum_{j=1}^{n} e_j^2$. This yields

$$L = \sum_{j=1}^{n} e_j^2 = \sum_{j=1}^{n} (Y_j - \beta_o - \sum_1^k \beta_i X_{ji})^2 \qquad \ldots.(3.5)$$

Eqn. (3.5) can be rewritten in matrix and vector notation as

$$\begin{aligned} L = \sum_{j=1}^{n} e_j^2 &= e^T e \\ &= (Y - X\beta)^T (Y - X\beta) \end{aligned} \qquad \ldots.(3.6)$$

The values of β_i that minimize L are the least-squares estimators and are obtained by equating the derivatives of L with respect to each β to zero. Thus

$$\left.\begin{aligned} \frac{\partial L}{\partial \beta_o} &= -2 \sum_{j=1}^{n} (Y_j - \hat{\beta}_o - \sum_{i=1}^{k} \hat{\beta}_i X_{ji}) = 0 \\ \frac{\partial L}{\partial \beta_1} &= -2 \sum_{j=1}^{n} (Y_j - \hat{\beta}_o - \sum_{i=1}^{k} \hat{\beta}_i X_{ji})\, X_{j1} = 0 \\ \frac{\partial L}{\partial \beta_k} &= -2 \sum_{j=1}^{n} (Y_j - \hat{\beta}_o - \sum_{i=1}^{k} \hat{\beta}_i X_{ji})\, X_{jk} = 0 \end{aligned}\right. \qquad \ldots.(3.7)$$

These equations may be recast into the *normal equations*:

$$n\hat{\beta}_o+\hat{\beta}_1\sum_{j=1}^{n}X_{j1}+\hat{\beta}_2\sum_{j=1}^{n}X_{j2}+\ldots+\hat{\beta}_k\sum_{j=1}^{n}X_{jk} = \sum_{j=1}^{n} Y_j$$

$$\hat{\beta}_o\sum_{j=1}^{n}X_{j1}+\hat{\beta}_1\sum_{j=1}^{n}X_{j1}^2+\hat{\beta}_2\sum_{j=1}^{n}X_{j1}X_{j2}+\ldots+\hat{\beta}_k\sum_{j=1}^{n}X_{j1}X_{jk} = \sum_{j=1}^{n}X_{j1}Y_j$$

....(3.8)

$$\hat{\beta}_o\sum_{j=1}^{n}X_{jk}+\hat{\beta}_1\sum_{j=1}^{n}X_{jk}X_{j1}+\hat{\beta}_2\sum_{j=2}^{n}X_{jk}X_{j2}+\ldots+\hat{\beta}_k\sum_{j=1}^{n}X_{jk}^2 = \sum_{j=1}^{n}X_{jk}Y_j$$

The equations may be solved to yield the *best linear unbiased estimators* when the errors e_i satisfy Eqn. (3.2).

The *normal equations* written in matrix form become

$$\begin{bmatrix} n & \sum_j X_{j1} & \sum_j X_{j2} & \cdots & \sum_j X_{jk} \\ \sum_j X_{j1} & \sum_j X_{j1}^2 & \sum_j X_{j1}X_{j2} & \cdots & \sum_j X_{j1}X_{jk} \\ \cdot & \cdot & \cdot & \cdots & \cdot \\ \sum_j X_{jk} & \sum_j X_{jk}X_{j1} & \sum X_{jk}X_{j2} & \cdots & \sum_j X_{jk}^2 \end{bmatrix} \begin{bmatrix} \hat{\beta}_o \\ \hat{\beta}_1 \\ \\ \hat{\beta}_k \end{bmatrix} = \begin{bmatrix} \sum_j Y_j \\ \sum_j X_{j1}Y_j \\ \\ \sum_j X_{jk}Y_j \end{bmatrix}$$

....(3.9)

or

$$S\hat{\beta} = g \qquad \text{....(3.10)}$$

The matrix S is called the matrix of *uncorrected sums of squares and cross-products*.

In normal computation methods S and g are readily set up in matrix form from the given data (e.g. for trend analysis, easting, northing and dependent variable). Using the relation

$$\hat{\beta} = S^{-1}g \qquad \text{....(3.11)}$$

the coefficient set β is determined by Gaussian inversion of the sums of squares matrix and subsequently solving for $\hat{\beta}$ using the matrix product of S^{-1} (the inverse of S) and g.

Usually for trend-surface analysis where a number of degrees of the polynomial expansion is required, the sums of squares matrix for the highest degree polynomial is constructed. This model is then solved according to Eqn. (3.11). For each lower degree polynomial the existing sums of squares matrix is truncated to the required degree, the new matrix inverted and new coefficients solved.

For each model and each set of coefficients, regression statistics (outlined below) are calculated to evaluate the statistical significance of the regressions.

An alternative and simpler method for the computation of coefficients is outlined in the next section. Although the alternate method was not used specifically in this study it has definite advantages over the inversion method in certain applications.

3.3.2 Gram-Schmidt Method

The algorithm for solution of the two dimensional polynomial model using the Gram-Schmidt method is given in detail in Crain & Bhattacharyya (1967). By this method a Gram-Schmidt orthogonalisation of the polynomial function system, which is non-orthogonal, is carried out with respect to the n data points.

Orthogonal functions are computed to yield an orthogonal set of polynomial coefficients.

The main advantage of this method is that the calculated coefficients are orthogonal. Hence only the highest degree polynomial need be calculated and to obtain the lower degree models, the redundant high degree coefficients are ignored. Coefficients determined by the inversion method are non-orthogonal and the low degree coefficients change with each new higher degree model. Consequently there is a much lower computational effort required to solve the orthogonal coefficients. Also for inspecting difference maps i.e. differences between successive trend-surfaces, the difference component for the orthogonal coefficients is a pure higher degree component whereas for the non-orthogonal coefficients the difference component only approaches a true difference component as the low degree coefficients are unequal. That is:

$$Z = \beta_o + \beta_1 X + \beta_2 Y \qquad \text{1st deg.}$$

$$Z' = \beta_o + \beta_1 X + \beta_2 Y + \beta_3 X^2 + \beta_4 XY + \beta_5 Y^2 \qquad \text{2nd deg.}$$

....(3.12)

Difference:

$$Z'-Z = \beta_3 X^2 + \beta_4 XY + \beta_5 Y^2 \qquad \text{Pure Quadratic Component}$$

....(3.13)

Non-Orthogonal Coefficients

$$Z = \beta_o + \beta_1 X + \beta_2 Y \qquad \text{1st deg.}$$

$$Z' = \beta_o' X + \beta_2' Y + \beta_3' X^2 + \beta_4' XY + \beta_5' Y^2 \qquad \text{2nd deg.}$$

....(3.14)

$$Z'-Z = (\beta_o'-\beta_o)+(\beta_1'-\beta_1)X+(\beta_2'-\beta_2)Y+(\beta_3'-\beta_3)X^2$$

$$+(\beta_4'-\beta_4)XY+(\beta_5'-\beta_5)Y^2 \qquad \text{Difference}$$

....(3.15)

The low degree terms will approach zero but not be equal to zero and hence this difference equation is only an approximate quadratic component.

Regression statistics are somewhat easier to calculate in the Gram-Schmidt solution than in the inversion method.

Although definite advantages exist in the orthogonal solution there are certain aspects of this method, when applied to the problems encountered in the present study, which prevent its application. The main disadvantage is that the independent variables require normalisation prior to the analysis. As the number of data points used for structure and thickness is at times unequal different normalisation parameters are required, and as a result the surfaces (i.e. coefficients) may not necessarily be directly comparable. Likewise difficulties may also arise in attempting to compare surfaces from successive units where the data point distribution differs.

For this reason the Gram-Schmidt solution is generally applied to problems where the control points are fixed and a number of different variables are measured or one variable is measured at all stations at successive intervals of time.

3.3.3 Statistical Measures

A number of simple statistics can be calculated from the trend-surface analysis to obtain information concerning the validity of the fitted surface and the proportion of the variation in the data explained by the trend-surface coefficients. These statistics include:

a) Total Variation: the total sums of squares of the deviations of the observed values from the mean.

b) Variation Not Explained: The variance component not accounted for by the trend-surface estimates of Z, i.e., the sums of squares of the difference between the observed Z and predicted Z values.

c) Variation Explained: The proportion of the total variation accounted for by the trend-surface estimates of Z, i.e., the difference between the total variation and the variation not explained.

d) Coefficient of Determination: A measure of the amount or 'goodness' of fit of a particular trend function and is the ratio of the variation explained by the surface to the total variation of the data.

e) Correlation Coefficient: Another measure of the degree of correlation between the observed values and the predicted trend-surface value. It is the positive square root of the coefficient of determination and is analogous to the correlation coefficient in the linear regression except that it can only range between 0 and +1.

f) F-ratio and Analysis of Variance: Used to test the statistical significance of the trend-surface at a given confidence level to determine the validity of the regression function against the hypothesis that the regression is due to chance alone. The value of F is given by the ratio of the mean sums of squares of the trend function to the mean sums of squares due to the residual component, i.e.

$$F = \frac{\sum(Z_{trend} - \overline{Z}_{obs})^2/m}{\sum(Z_{obs} - Z_{trend})^2/(n-m-1)} = \frac{\text{Variation Explained}/m}{\text{Variation Not Explained}/(n-m-1)}$$

where m = degrees of freedom of trend (no. of coefficients excluding constants)

(n-m-1) = degrees of freedom of residuals (n is no. of data points)

The calculated F-ratio is then compared with tabulated F-test values at a given confidence level to establish the significance of the trend. Apart from the total F-ratio based on all the coefficients of the regression function, an incremental F-ratio can be calculated for the additional terms added with each degree of polynomial. This F-ratio determines the statistical significance of any improvement in the fit of the added terms.

Various workers (e.g. Parsley, 1971) use the statistical significance of the added terms to establish the reduction of the systematic variation in the data such that the residual variation is randomly distributed about the regression function. The highest degree function whose added terms (i.e. the highest degree terms) significantly improved the fit is taken as the trend-surface equation. Although for non-areally distributed data the F-ratio will indicate whether the residuals are normally distributed about the trend and hence satisfy the theoretical regression condition of Eqn. 3.2, this test does not necessarily apply to geographic data. Cook (1969a), for example, shows residual maps derived from trend-surfaces selected on the basis of the F-ratio which indicate high local serial autocorrelation in the residuals and hence not in accordance with the condition of Eqn. 3.2.

The inability of the incremental F-ratio test to indicate whether all the serial autocorrelation has been removed from the data for a given regression is probably due to the variance of the data changing over the map area (Koch and Link, 1971). The problem of deciding which trend-surfaces to use for interpretation purposes is elaborated in detail in the following section.

3.3.4 Types of Trend-Surface Analysis

The selection of trend-surfaces is closely tied to the aims and logical approach of individual workers to the method of trend-surface analysis.

Total trend-surface analysis, on one hand, aims to account for all the non-random areal variation in the given data using the maximum degree of polynomial whose residuals are randomly distributed about the trend-surface (Parsley, 1971). All the systematic variation in the data will be expressed by the resulting mathematical function. It will include the systematic local features as well as the regional components of variation.

Partial trend-surface analysis involves the use of surfaces of lower degree than the surface of maximum fit and aims to define, on a quantitative basis, simple geometric components in the data. These components may be considered analogous to regional geological elements at different levels of complexity (Krumbein, 1959; Krumbein & Graybill, 1965). Residuals from these low degree surfaces which do not account for all the non-random variation in the data will be locally autocorrelated. Partial trend-surface analysis is therefore a breakdown of the data into discrete *regional* and *local* components which in turn may be related to geological features of regional and local interest.

In the study of the variation in the geometry and structure of the lithosomes of the M.I.B. partial trend analysis has been used to analyse and isolate the regional and local components in the data.

Discussion of the relative merits and validity of both total and partial trend-surface analysis has been partly confused by a number of authors (e.g. Chayes & Suzuki, 1963; Baird *et al.* 1971; Draper & Smith, 1967; Chayes, 1970) not taking into full account the specific problems to which each method is applicable. Criteria for the choice of particular trend-surfaces is also involved especially in regard to total trend analysis. Total trend-surfaces may be considered as 'predicting surfaces' rather than expressions of a true regional component which extends over the entire map area. Parsley (1971) maintains that the trend-surface (implying total trend) should contain both the regional and non-random local variation. Residuals from Parsley's trend-surface should be randomly distributed 'noise' having a low serial auto-correlation. For data whose variance was constant over the map area an F-ratio test would result in a suitable selection of the trend-surface according to the procedure of 3.3.3(f). However for data with a non-constant variance (heteroscadistic) the residuals from the trend-surface selected on the criteria of the significance of added terms may still have a high autocorrelation and hence not satisfy the regression criteria of Eqn. 3.2. Parsley (1971) attempted to test this effect by calculating serial autocorrelation coefficients from his residuals and hence further check the validity of his trend-surfaces.

Other approaches to total trend-surface analysis include that of Miesch and Connor (1968) who used a stepwise regression procedure. Polynomial terms up to fifth degree, as well as logarithmic, exponential, and reciprocal terms could be individually tested to determine whether the inclusion of each term significantly improved the fit to the data at a predefined confidence level. Hence the trend-surface equation accounted for the maximum amount of variation with the available terms and redundant terms were not included. Miesch and Connor (1968) also pointed out a major problem associated with the maximum fit approach to trend analysis in that large numbers of coefficients are usually required to account for all the systematic variation. Thus in the sums of squares matrices very large numbers will be set up and upon inversion, round-off errors may occur leading to erroneous coefficients. A further source of error in sums of squares matrices may also result from very poorly conditioned data point distributions which in extreme cases may cause a 'blow-up' state in the matrix inversion. In order to measure the degree of conditioning in the sums of squares matrix they used the determinant of that matrix to derive a condition value which could be used to assess the stability of the coefficient set. A variety of extreme data distributions were tested to determine the effects of such distributions on the condition value and they found that the condition-values of the large sums of squares matrices were very sensitive to biased and clustered data distributions.

Harmonic regression analysis in which Fourier terms are used instead of simple polynomials (e.g. James, 1966) may be considered a total trend-surface technique where all periodic systematic variation is included in the trend-surface. The method is not particularly relevant to partial trend analysis as linear dip components must be removed from the data before the regression analysis and wavelengths of the periodic functions must be specified. Further discussion of harmonic trend-surface analysis is given in Harbaugh and Merriam (1968).

The total trend-surface analysis concept has been taken to an extreme by Cole (1969). He attempted to derive a surface which closely approached a total fit surface (i.e. residual variance approaching zero) and could be used as a conventional contour interpolation map. An iterative system of quadratic weighting based on an initial trend-surface approximation to the data was used and iteration was continued across the interpolation grid until the non-random variation in the residuals was minimised. Residuals from Cole's trend-surface contain no local autocorrelation and hence are of little value for outlining domains of local variation in the data.

Krumbein (1959) and Merriam and Harbaugh (1964) in early work using trend-surface analysis applied to stratigraphic data were however specifically aiming to analyse their data into large-scale *regional* and small-scale *local* features. The partial trend-surface analysis approach in such case aims not to remove all the systematic and small-scale local features. This partial trend-surface analysis approach, which has also been used in the present study, aims not to remove all the systematic variation in the data but to isolate regional geological *trends* from features which may be of local geological significance. The local (residual) components will contain all the random variation in the data as well as the auto-correlated local variation.

Higher degree surfaces generated in total trend analysis are of minimal importance to the analysis of the M.I.B. data as these surfaces can scarcely be regarded as *trends* and their residuals contain no meaningful geological component. For stratigraphic data each low degree surface is of relevance as it represents an element of the regional variation. Thus for structural data of a particular formation a homoclinal dip can be identified from the first degree trend-surface; a second degree surface will be the sum of the homoclinal dip component and a simple fold component. Difference maps between successive trend-surfaces (e.g. as in Eqn. 3.15) are likewise useful in isolating the higher degree components of the added terms. Hence by removal of simple lower degree surface the 'pure' fold component in the higher degree surface may be inspected.

In the Sydney Basin it is likely only fairly simple structural controls operated to affect sedimentation and in this regard the complex high degree trend-surfaces may not be geologically relevant. The regional geological constraints on the upper limit of the degree of trend-surface which can be meaningfully calculated apply both to the thickness variations (possible indicators of Permian structure subsidence) and present-day structure.

While F-ratio tests (Sec. 3.3.3(f)) are often unsuccessful indicators of whether the systematic variance has been removed from the residuals the tests may still be used to assess the statistical significance of the partial trend-surfaces and their added terms. Only statistically significant trend-surfaces have been discussed in this study as representing possible regional geological trends. Due to the very high serial autocorrelation present in the M.I.B. data the configuration and location of residual domains varies only slightly from each trend-surface and hence residuals from each degree trend have not been discussed.

3.3.5 Trend-Surface Analysis Program Used in this Study

The trend-surface analysis program used in this work is a modified version of a generalised multiple regression program by Esler, Smith & Davis (1968). This program was modified to include a Gram-Schmidt solution as well as the matrix inversion solution; the data structure was simplified such that regression could be carried out by specifying the highest degree of polynomial required rather than specifying each individual. Other modifications include initial sorting of the data and internal storage of residuals such that the output, in one data set, contains all the residuals and can be directed to the printer, punch and/or tape. These changes facilitate deck set up and handling of output for further analysis. Numerous minor modifications were made to accommodate the program on the IBM 360/50 at the Computing Centre, the University of N.S.W.

The program performs a regression analysis, in this case, with the independent variables and up to seventh degree, lists residuals, statistics of the regression, a line-printer plot of the trend-surface map, the original data, and the residuals, at any desired scale. A generalised flowchart is given in Figure 3.3. Execution time for establishing the sums of squares matrix and deriving the coefficient set by matrix inversion is generally less than 20 seconds, depending on the maximum degree required. Time required for plotting each trend map and the data and residual plots is of the order of 2-3 minutes,

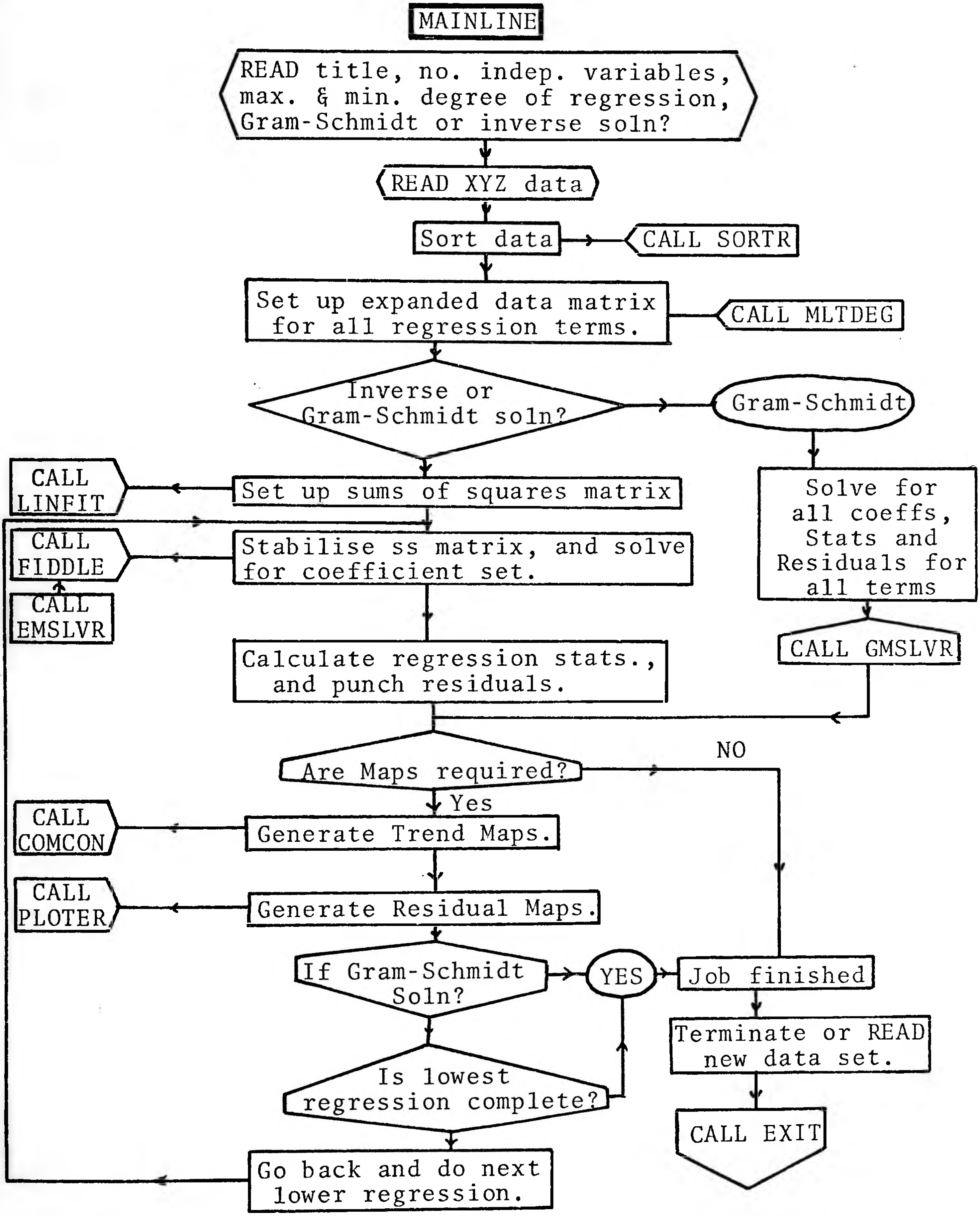

FIGURE 3.3 Simplified flowchart of trend-surface analysis program

depending largely on the map size required. In production runs output consisted of trends 1st to 4th degree, statistics, residuals and trend-surface maps. The data plots were not used as these were plotted and contoured on a drum plotter from the residuals in the form of card output. A full run on the twenty eight data sets used (thickness and structure for up to 103 points) took 80 minutes of C.P.U. time and 280K bytes of storage.

3.4 CONTOURING OF AREAL DISTRIBUTED DATA

In order to handle the large quantity of maps generated by the trend-surface analysis it was desirable to machine contour raw data and residual maps. Apart from the obvious problem of the volume of drafting effort the objectivity and consistency of the automatically contoured maps would prevent any interpretive bias which may be introduced in hand contouring.

Crain (1970) has summarised the various procedures and algorithms available in setting up a contouring program. Early methods were dependent on inverse weighting functions; they were fast but produced very noisy contour patterns in areas of poor control. Later programs used piecewise mosaiced polynomials over the map area to set up the contouring grid (e.g. McIntyre, Pollard & Smith, 1967). These, however, are most unreliable in areas of poor point control and may produce spurious maxima or minima. Bicubic spline algorithms (Alberg, *et al.*, 1967) have been used more recently for gridded data (Bhattacharyya, 1969); they produce reasonably smooth maps and overcome most problems, but are very time-consuming.

Finite difference methods assume that the contour surface obeys some differential equation. Finite difference formulae are then used to approximate this differential equation and solved iteratively. One new method developed by Briggs* (pers. comm.) using finite difference techniques assumes that the interpolated surface satisfies the fourth-degree equivalent of the La Place Equation

$$\text{i.e.} \qquad \frac{d^4z}{dx^4} + \frac{d^4z}{dy^4} = 0 \qquad \text{....(3.16)}$$

The resulting surface is the surface of maximum smoothness. The contour surface will pass through all data points and have the minimum of inflexion points in the contours between the control points. This method uses a series of finite difference formulae to smooth an initial estimate of the interpolated contouring grid to a convergence point where the maximum smoothness criteria are effectively obeyed. For the initial estimate array the z value at each data point is spread to adjacent grid points; the smoothing subroutine then removes introduced noise between data points.

The basic routine for the initial estimate grid and the smoothing were obtained from Briggs* (pers. comm.); a program to work out contour line cuts through the interpolated grid was obtained from Palmer (1970). Subroutines were written by

*1970. Bureau of Mineral Resoures, Canberra.

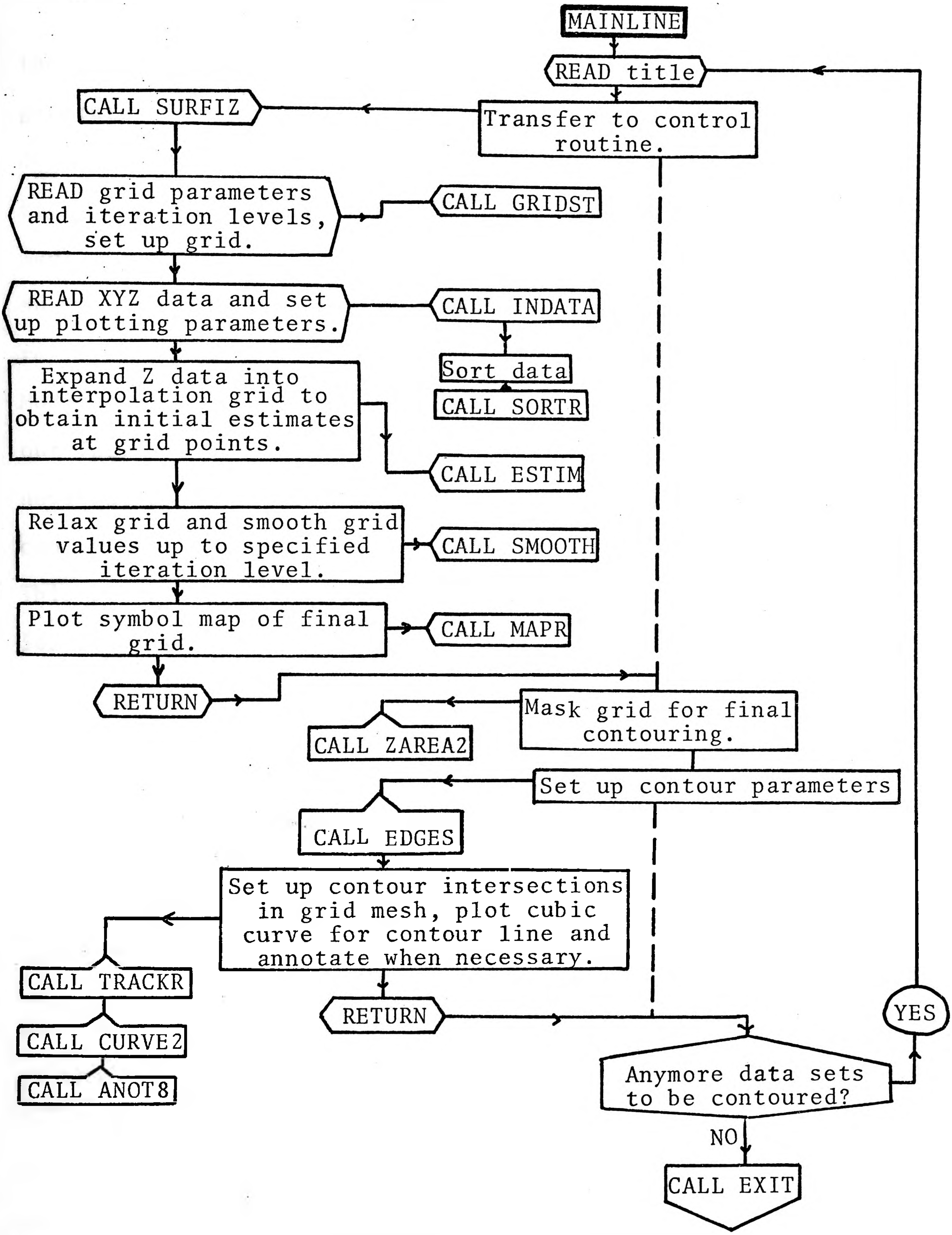

FIGURE 3.4 Flowchart of contour interpolation program

the present author to generalise and sort the input data, to generate curved contour lines, annotate contour lines, to define the control area and restrict contouring to this area and permit alternative line printer output of the contour map. Also the efficiency of the initialising and smoothing subroutines of Briggs has been increased with judicious reprogramming. Array storage was also reduced by 25%. Modifications to the contour tracking routine include a blocking out facility such that certain areas need not be contoured if desired, and contour line density control to eliminate over-contouring. A flowchart of the program is given in Fig. 3.4. This program was used in conjunction with an off-line CALCOMP 565 10" drum plotter.

3.5 ANALYSIS OF RESIDUALS AND MAP COMPARISON

Trend-surface analysis of the thickness data of a given unit should reveal certain information as to the pattern of contemporary basin subsidence at both a regional and local scale. Analysis of structural data resolves the present-day structure. In order to identify the Permian structures which have been intensified, from subsequent deformations, comparison of the analysed data at both the regional and local level must be undertaken. Trend-surfaces were compared visually on a basis of the similarity of directional features which were resolved in the trend-surfaces. A number of independent methods were used for the comparison of the residuals from the thickness and structure of each unit.

Cook (1969a) used linear correlation and match matrices of the signs of the residuals to assess the degree of correspondence between positive and negative structure and thickness residuals in a similar study on the persistence of Permian structure on the Southern Sydney Basin. Matching coefficients for structure residuals of successive formations in Kansas were calculated by Merriam and Lippert (1966) to determine similarities between trend-surface residuals. Merriam and Sneath (1966) derived cluster diagrams from matrices of linear correlation coefficients and Euclidean distance coefficients to further give a more detailed analysis of the relationships between structural surfaces in Kansas.

3.5.1 Linear Correlation

Linear correlation coefficients (Pearson product-moment) of the residuals of both the structure and thickness variables for each stratigraphic unit were calculated for each degree trend. Data were standardised prior to each linear regression such that the transformed data had a mean of zero (0.0) and standard deviation of one (1.0). This was done to guard against weighted correlations due to scale effects between the variables. The linear regressions were carried out between the raw thickness data and residual thicknesses against the four residual structure data and results for each regression plotted on a graph plotter over a range of three standard deviations.

Results were condensed to a correlation matrix of the form

	Residuals			
	1st Structure	2nd Structure	3rd Structure	4th Structure
Raw Thickness	r_1	r_2	r_3	r_4
1st Thick. Residual	r_5	r_6	r_7	r_8
2nd. Thick. Residual		r_9	r_{10}	r_{11}
3rd Thick. Residual			r_{12}	r_{13}
4th Thick. Residual				r_{14}

TABLE 3.1

The lower half of this correlation matrix was not calculated as it is most likely that the present structure is an intensification and a complication of the Permian subsidence patterns. Hence the thickness residuals will only indicate geologically valid correlation with structure residuals of the same or higher degree.

A Student's t-test was carried out on the correlation coefficients at a 95% confidence level to assess the significance of the relationship between the sets of residuals.

3.5.2 Cluster Analysis

Linear correlation matrices were also calculated for the raw thickness and residual thickness for each formation studied in order to determine relationships between the thickness patterns of successive formations. Five correlation matrices were calculated, one each for the raw thickness data and the four thickness residual data sets. A program written by the author to handle data arrays with missing values (since each formation has a different number of data points), was used for the computation of the correlation matrices. Cluster analysis was then carried out on all the matrices to emphasise the relationships between the variables (formation thicknesses) graphically. Matrices were converted to distance matrices by an arc cosine transformation and dendrographs (McCammon, 1968) were computed using a program adapted after McCammon, (1970).

3.5.3 Match Count Matrices

These are simple tally matrices whereby the signs of the residuals of structure and thickness are classified into the following groups for each formation.

Structure Positive - Thickness Positive	(a)
Structure Positive - Thickness Negative	(b)
Structure Negative - Thickness Positive	(c)
Structure Negative - Thickness Negative	(d)

TABLE 3.2

For contemporary Permian structures to be preserved in the present structure, the matrix should be weighted towards (b) and (c) of Table 3.2. The results of these counts have been expressed as a percentage of the sum of data points in the (b) and (c) categories and recorded in a matrix of the form of Table 3.1. Chi-squared tests using Eqn. 3.17 were carried out to determine the statistical significance of any weighting obtained.

i.e. $$\chi_{\nu}^{2} = \sum_{i=1}^{2} \frac{(f_i - e_i)^2}{e_i} \qquad \ldots.(3.17)$$

$\nu = 1$ (degrees of freedom)

f_i...observed frequency

e_i...expected frequency.

The matrix of Table 3.2 was condensed to a two element matrix by summing (a) and (d), and (b) and (c). The binomial test was also applied. The expected frequency for a random situation would be 50% in each element for both tests.

3.5.4 Match Maps

While the above methods provide insight into the residual relationships at an absolute level, they convey no information as to the areal variation of the strength of the relationship. Although spectral and cross-spectral methods may be useful in the future for this type of comparison at present the mathematics have not yet been sufficiently developed to handle irregularly spaced data (vide, Corbyn, 1971).

The method used in this study to include geographic variation in the relationships is quite simple. Firstly data are transformed such that the positive residuals of both data sets being matched range from 0 to +1, (by dividing by the maximum positive residual in each set), and that the negative residuals range from -1 to 0, (by dividing by the minimum residual in each set). The transformed residuals of both sets will now have identical ranges and the scale is preserved. At corresponding points the new residual values are then *added* together. The resulting map is effectively the sum of the structure residuals and the thickness residuals. Although there is a random component in the residuals, especially with the thickness variation the resultant map should reveal localised areas where the relations between the residuals are strongest i.e. areas where the summed variable is closer to zero would indicate a local strengthening in the relationship as in (b) and (c) of Table 3.2. Values approaching ±2.0 would indicate direct relationships rather than the inverse case; intermediate values indicate a more random relationship. This method relies heavily on the presence of autocorrelated residual domains in that these domains should persist when the residuals are added and thus be identifiable on a map.

3.6 MARKOV CHAIN ANALYSIS

An objective and independent approach to the vertical lithological variation of a sedimentary sequence is to use an embedded first-order Markov chain model. It is a semi-probabilistic model for structuring the observed succession of lithologies to reveal the major transition patterns in the succession; transitions from one lithology to another are dependent only upon the immediate previous event (i.e. lithology). The method of deriving the Markov chain has been outlined by Gingerich (1969) and is reviewed here. A program to carry out the following procedure was written by the present author. Execution time was less than a minute for the tally matrices run. A flowchart is given in Fig. 3.5.

A simple matrix notation is used to facilitate the analysis. For a succession where four different lithological states (e.g. L_1, L_2, L_3, L_4) and p_{ij} is the probability of changing from one state L_i to state L_j, then the probabilities for all possible transitions may be structured in matrix form:

$$\begin{array}{c|cccc} & L_1 & L_2 & L_3 & L_4 \\ \hline L_1 & p_{11} & p_{12} & p_{13} & p_{14} \\ L_2 & p_{21} & p_{22} & p_{23} & p_{24} \\ L_3 & p_{31} & p_{32} & p_{33} & p_{34} \\ L_4 & p_{41} & p_{42} & p_{43} & p_{44} \end{array} \qquad \ldots.(3.18)$$

i.e. if L_2 is sandstone and L_3 is claystone then p_{23} is the probability that a sandstone is overlain by a claystone. The major diagonal elements for an embedded model will be zero as changes in the same state are not recorded. This matrix is known as the *transition probability matrix* and is the observed *tally matrix* of all transitions expressed in probability form.

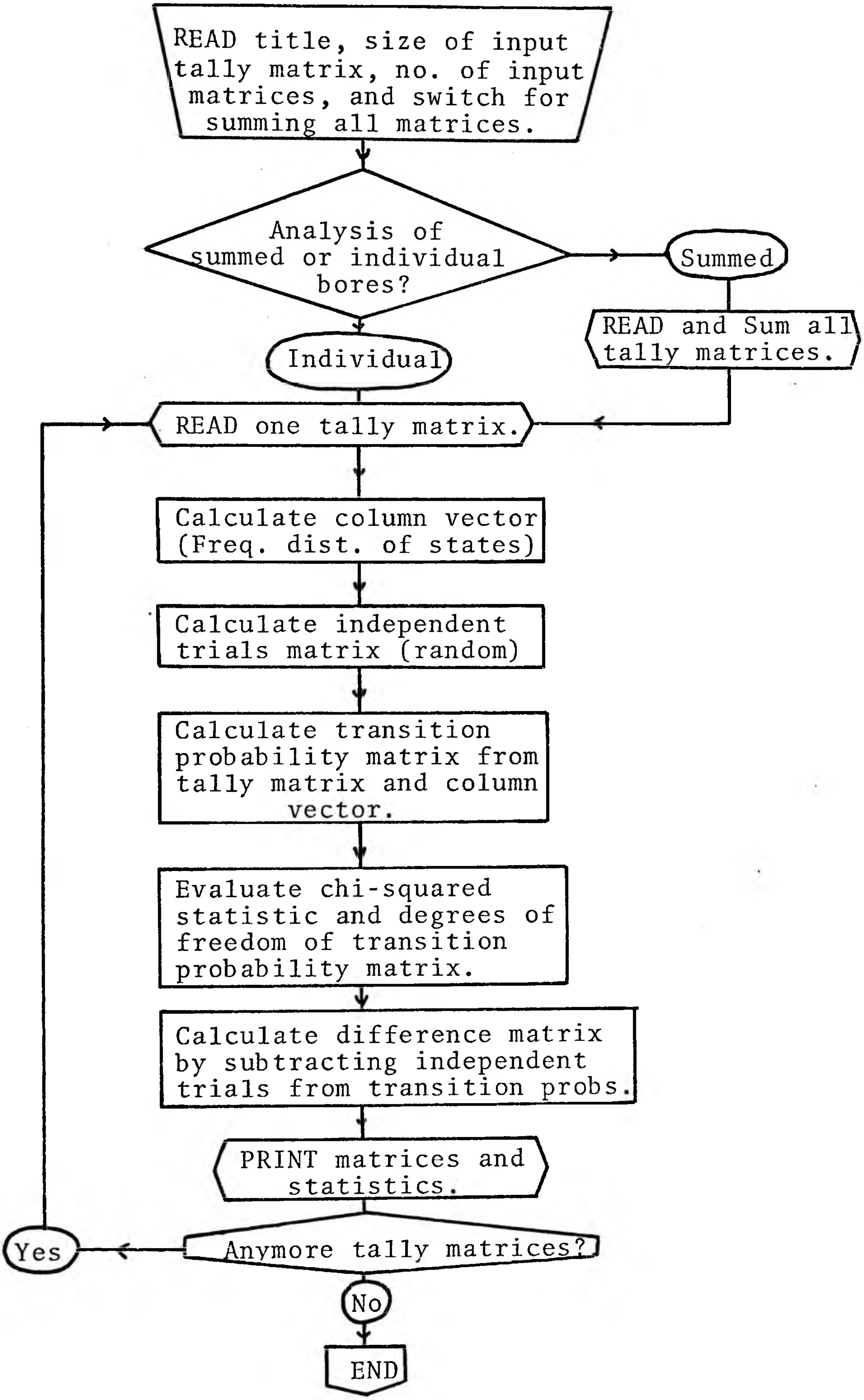

FIGURE 3.5 Flowchart for Markov chain analysis program

Each particular transition element (p_{ij}) is derived from the tally matrix by dividing that particular element by the sum of all transitions for that row in which the element occurs.

From the tally matrix the elements in each row can be added to yield a *column vector* which gives a frequency distribution of the number of individual beds of each lithology present. A further matrix, an *independent trials matrix*, can be calculated on the assumption that the sequence of rock types was determined randomly within this frequency distribution. The independent trials probability is obtained by dividing the particular element in the column vector of the underlying lithology by the difference between the total number of beds minus the column vector element of the underlying lithology.

When the independent trials matrix is subtracted from the transition probability matrix, a matrix with both positive and negative elements is obtained. This is the *difference matrix* and as Gingerich (1969) states is ". . . the positive elements represent those transitions which have a higher than random probability of occurring. A fully developed cycle can be derived by following the positive difference through the matrix."

Billingsley (1961) proposes the chi-squared statistic to determine if the tally matrix is the result of a random process

$$\chi_{\nu}^2 = \sum_j \frac{(f_{ij} - f_i . e_{ij})^2}{f_i e_{ij}} \qquad \ldots .(3.19)$$

where

f_{ij} = transition prob. matrix

f_i = freq. distribution of states

e_{ij} = independent trials matrix

ν = degrees of freedom

This statistic is quite valid although some doubt as to its use occurs with fairly small sample spaces, say less than twenty five transitions, where the χ^2 value is dependent upon the thickness or complexity of the section from which the tally matrix was derived. The number of degrees of freedom for the matrix is determined by the number of non-zero entries in the independent trials matrix when an embedded model is used.

CHAPTER 4

VERTICAL VARIATION IN THE MOON ISLAND BEACH SUB-GROUP

4.1 INTRODUCTION

In order to compliment the analysis of the geographic variation provided by the use of trend-surface techniques on data from successive stratigraphic units the vertical lithological variation has been studied. The assumption is made in this section that the total thickness of the M.I.B. is an expression of the overall Permian subsidence pattern for the given interval. No distinction has been made between tectonic structural subsidence and ephemeral compaction structures although the results of trend analysis (presented in Chapter 5) indicate that the tectonic subsidence was the predominant influence on deposition over a long period of time (i.e. of the entire M.I.B. section). The vertical lithological variation has been analysed to assist interpretation of the depositional environment with energy extremes between conglomerate sedimentation and peat swamp conditions and to examine the relationship between the type of lithological variation and the structural environment.

Studies of the vertical variation of sedimentary successions are in many cases concerned with the identification of repetitive sequences of lithological types in a particular order. Repetitive sequences have been variously termed cycles

(Duff *et al.*, 1967), cyclothems, (Weller, 1958) and rhythms (Fearnsides, 1950). Weller (1958) proposed the term *cyclothem* for the actual rock unit sequence which is repeated and it seems reasonable to extend the definition of the term to other lithological sequences (i.e. non-Pennsylvanian cyclothems where marine formations are absent) and to cases where sequences are imperfectly developed. The terms *cycle* and *rhythm* cause complications of definition especially when applied in respect of symmetry and asymmetry of a sequence. Thus some workers would call a symmetric sequence of the type *abcdcba. abcdc*..., 'cyclic', and an asymmetric sequence of the type *abcd.abcd.*, 'rhythmic' or 'pulsatory'.

In the M.I.B. symmetric sequences are virtually non-existent. The term 'cycle' is applied here to imply an *abcd* sequence or an ordered subset of this sequence e.g., a fining cycle *abc* occurring in a general repetitive asymmetric sequence of cyclothems (i.e. abcd.abcd.bcd.abcd.abc. etc.). No inference of symmetry or of regeneration of another cycle is intended. Hence *cycle* in this study may be regarded as a less formal but parallel term to Weller's original *cyclothem*. Duff and Walton's (1962) *ideal cycle* is used as a basis for the analysis of cycles in the M.I.B. although the term should be applied only as a generalised hypothetical description of real (cyclic) sequences. Unless the variation of the sequences from the ideal cycle is taken into account an oversimplification of the model to explain cyclothem development may result. The *modal cycle* (Duff & Walton, 1962) is perhaps more relevant to the results of statistical analysis of cyclic sequences; the modal cycle should approach the most probable transition path determined in a Markov Chain analysis of the sequence.

The semantics of terminology of cyclic sedimentation have been frequently discussed and for a detailed evaluation of different nomenclatures *vide* Duff, Hallam and Walton (1967). In discussing other work terminology has been adapted to that used for the M.I.B. sequences.

The M.I.B. lithological sequences have been analysed by Markov Chain analysis and cycle frequency analysis, the former method being fairly definition-independent while the latter in part depends on the definition of what can be considered as a cycle.

Most of the early work on cyclic sedimentation (e.g. Weller, 1930) has been in relation to Carboniferous sequences, usually coal-bearing, but in many cases containing marine limestone horizons. This has now extended to a number of different types of sequences (Duff *et al.*, 1967) including the Permian coal measures of the Sydney Basin.

An extensive literature has developed concerning the recognition of cycles or cyclothems in the Permian coal measures of New South Wales. However, as Duff (1967) and Loughnan (1966a) have pointed out, these successions do not strictly meet the criteria for cyclothems as proposed by, for example, Weller (1958). Rattigan (1966) used the term cycle in describing fining-upwards sequences in the Newcastle Coal Measures of the Sydney Basin, New South Wales. Duff (1967) discussed the possibility of defining cycles based on fining-upwards sequences in the Newcastle Coal Measures of the Sydney Basin, New South Wales. He rejected the idea because there were, in many cases, coarsening-upwards sequences below the coarsest unit. Duff (1967), however, did apply the term 'cycle' to units with the boundaries defined by coals in all cases, so that each unit consists of a clastic* bed, or sequence of clastic beds, overlain by a coal seam.

Booker (1960), commenting on the "almost infinite variation of the sequence" added: "It is not uncommon to find a conglomerate overlain immediately by a shale and coal horizon, the sandstone being missing, or a sequence of sandstone, shale, coal, without conglomerate. This feature also applies to the cycles in which only the fine facies are developed". Duff (1967) studied this variation by determining the frequency of each combination of interseam strata. The interpretation of the meaning of this frequency data is limited by the constraints imposed by his initial definition

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*The term clastics here refers only to inorganic epiclastics. Organic epiclastics may be important in some sequences but will not herein be distinguished from autochthonous organic material.

of the cycle.

The recognition of cycles presents little difficulty with successions such as those in the Carboniferous of Europe and North America which contain marine limestones or clastics, freshwater clastics, and coal seams. That such cycles are geologically significant is also undoubted even though there is controversy over their origin. With the New South Wales Permian coal measures the alternation is generally between coal and freshwater clastics and is statistically meaningless although it still has some geological significance inasmuch as alternating lithologies must be due to changes in depositional conditions. To obtain a statistically non-trivial result either the clastics or the coals must be divided into at least two different lithologies. Given this further division it is possible to determine if statistically significant patterns are present within the successions. Geological interpretations of these patterns may then be attempted.

4.2 DATA USED FOR ANALYSIS OF VERTICAL VARIATION

The location of bores used in this chapter are given in Fig. 4.1. Although a large number of bores was available for the analysis of the vertical lithological variation the clastic sequences in a large number of the bores were not logged in sufficient detail to be analysed reliably. The bore sections employed were those which separately recorded and described most of the lithological changes in the clastic formations.

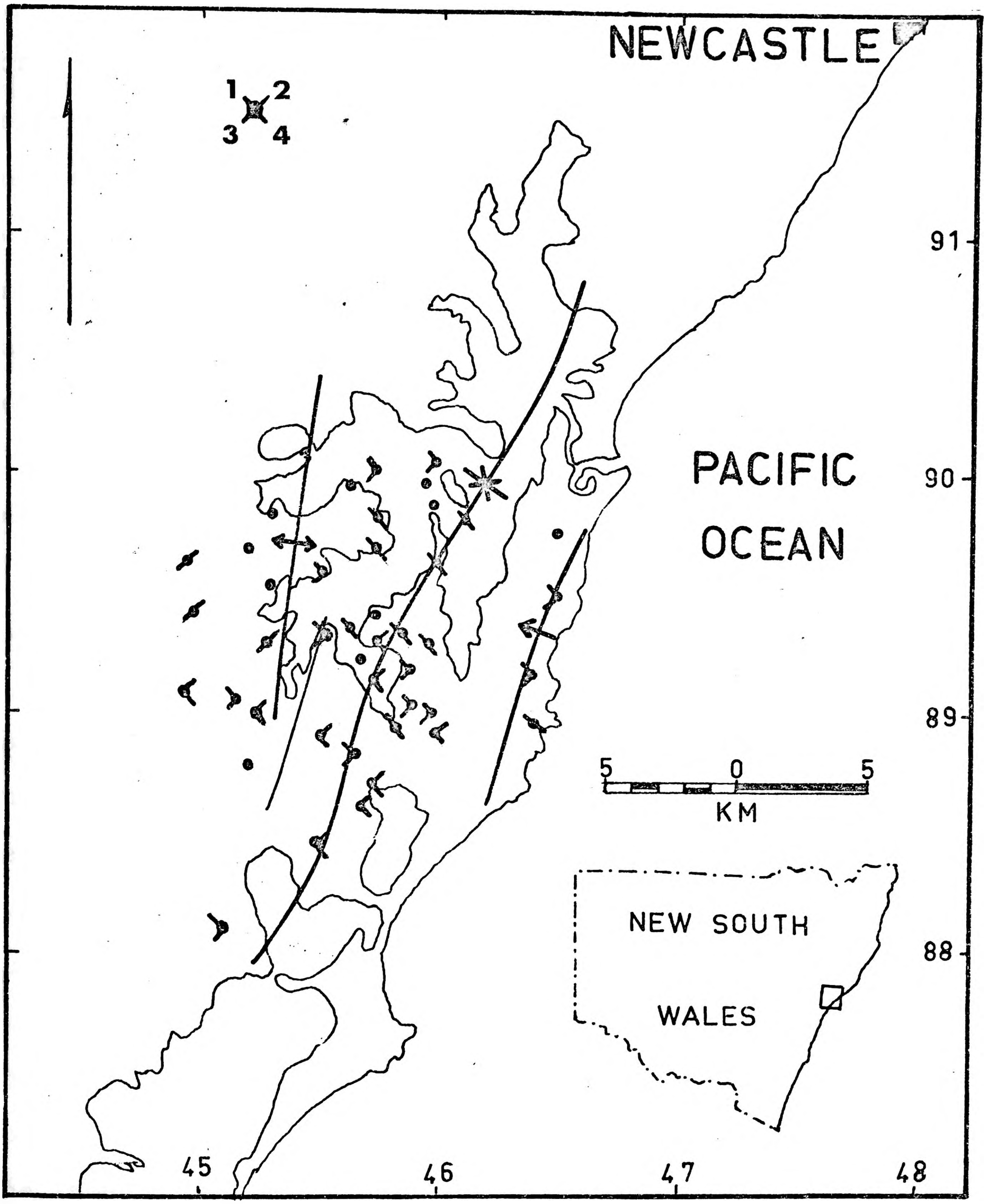


FIGURE 4.1 Locality map showing the structure of the Macquarie Syncline and borehole locations. Borehole symbol codes refer to the most probable transition matrix modes in Table 4.3.

For example the Teralba Conglomerate Member was frequently described as conglomerate containing minor sandstone beds; such a description was considered inadequate and the bore rejected. Markov chains were derived for thirty seven bores and the cycle frequencies of these and eight additional bores calculated. The slightly lower tolerance level of acceptance for the cycle frequencies was due to the sandstone-conglomerate alternations not being of specific importance to the definitions adopted for a cycle.

4.3 MARKOV CHAIN ANALYSIS

The use of a first-order Markov chain model offers an objective approach to the analysis of sedimentary successions and avoids the problem of defining a cycle before the data can be analysed. The Markov chain model is of a semi-probabilistic type and provides a device for structuring an observed succession. In particular it shows the dependence of one state upon the preceding states. With a first order Markov chain, transitions from one lithology to another are tested to show the extent a particularly lithology is determined by the immediately previous lithology. The computation methods used for the preparation of the Markov chain analyses is given in Section 3.5. Kemeny and Snell (1960) give an introduction to the mathematics of Markov chains while Vistelius (1949) and Vistelius and Faas (1965) used Markov chains for describing and analysing sedimentary cycles. Krumbein (1967, 1968) has discussed the application of Markovian models to studies of cycles particularly in relation to simulation experiments. Krumbein mainly used fixed interval sampling to generate the data but also (Krumbein, 1967) described the compilation of the tally matrix from lithology transitions. Krumbein and Dacey (1969) discussed the characteristics of the embedded Markov model which is used if multistory lithologies are not distinguished in compiling the tally matrix from lithology transitions. Gingerich (1969) used lithology transitions for the compilation of the tally matrix for a fresh water sequence of sandstone, shale, lignite and limestone. From the positive elements of the difference matrix he deduced "a fully developed cycle". This is obtained by the linking of the transitions with the greatest marginal probability (i.e. actual probability of the transitions minus the probability if the transitions were random).

The M.I.B. succession can be considered as fitting a stationary non-ergodic model.

4.3.1 Data Analysis (Markov chains)

For the Markov chain analysis various preliminary models and criteria were tested in an attempt to avoid obtaining trivial results. Data were examined from both graphic logs and original written logs of thirty seven of the bores to determine whether the filtering of the data (i.e. possible non-significant transitions) provided by a graphic log helped clarify the order in the sequence of transitions. However the detailed written lithological log was accepted as the source of data due to the inconsistencies in the accuracy and detail in the available graphic logs. Minimum thicknesses were selected and imposed on the transition data from the written logs thereby providing an arbitrary control over the removal of non-significant lithological transitions.

Five state and four state models were tested using the following lithologies:

Five State Model	Four State Model
Coal	Coal
Carbonaceous shale	Claystone
Claystone	Sandstone
Sandstone	Conglomerate
Conglomerate	

With the four state model, the carbonaceous shale lithology was included in the claystone state. The data were extracted using five different lithologies with carbonaceous shale being a sub-division of the fine clastic sediments which often underlie the coals. However the carbon content of the sediments logged as carbonaceous shale varies widely depending on the definition adopted by the geologist logging the core. To obtain the four state data the carbonaceous shale transitions in the tally matrix were added to the claystone transitions. The claystone-carbonaceous shale and the carbonaceous shale-claystone transitions were zeroed to give equivalent four-state data.

Both data sets, i.e. five- and four-state matrices, were processed and it was found that with the additional lithology in the five state model (thereby adding another eight transition elements) the available number of transitions gave unacceptably sparse matrices. In view of this and the doubtful reliability of the carbonaceous shale category the sub-division of the fine clastic lithologies was not adopted and the four state model was used, i.e. conglomerate, sandstone, claystone, and coal. Lithologies were defined with the following minimum thicknesses:

Lithology	Thickness
Coal	2 ins (0.05m)
Claystone	1 ft (0.3m)
Sandstone	2 ft (0.6m)
Conglomerate	5 ft (1.6m)

These thicknesses were chosen to give approximate equivalence to each lithology in terms of depositional significance.

A tally matrix was extracted for each bore from the written log. These matrices were processed individually, with a separate transition probability and difference matrix being derived for each bore, and collectively with all bores being summed into one matrix and the transition probability and difference matrices being determined. From these matrices the most probable paths through the matrices were established and the bores broadly grouped on this basis.

4.3.2 Results of Markov Chain Analysis

The transition probability and the difference matrix for all the bores (Table 4.1) indicates that the most probable transition path for lithological changes is a fining-upwards sequence from the coarsest lithology to the intermediate and fine clastic lithologies and thence oscillating transitions between coal and claystone. The transition from coal to coarse clastics is not the most probable event after a coal seam and in this respect the matrix does not generate a repetitive succession. It is, however, the second most likely alternative and eventually reversion to coarse epiclastics occurs and another fining-upwards sequence is initiated.

This path in the transition matrix is very similar to Gingerich's (1969) fully developed cycle and could be diagrammed:

$$\begin{tikzcd} \text{Conglomerate} \arrow[r] & \text{Sandstone} \arrow[r] & \text{Claystone} \arrow[r, shift left] & \text{Coal} \arrow[l, shift left] \arrow[lll, dotted, bend left] \end{tikzcd}$$

Inspection of the matrices for individual bores shows that matrices can be recognised ranging between a simple fining-up sequence and a sequence where oscillations mask any directional trend in the sequence. A breakdown was made of bores into those which show a fining-upwards sequence and those which have a tendency to oscillate between clastic lithologies, and between fine clastics and coal. From Table

TABLE 4.1 - CALCULATED MARKOV MATRICES FOR ALL BORES

TALLY MATRIX

	CONGLOMERATE	SANDSTONE	CLAYSTONE	COAL
CONGLOMERATE	0.0	82.0	38.0	0.0
SANDSTONE	54.0	0.0	85.0	4.0
CLAYSTONE	38.0	52.0	0.0	125.0
COAL	42.0	29.0	95.0	0.0

INDEPENDENT TRIALS MATRIX

CONGLOMERATE	0.0	0.272	0.410	0.318
SANDSTONE	0.239	0.0	0.428	0.333
CLAYSTONE	0.279	0.333	0.0	0.388
COAL	0.251	0.299	0.450	0.0

TRANSITION PROBABILITY MATRIX

CONGLOMERATE	0.0	0.683	0.317	0.000
SANDSTONE	0.378	0.0	0.594	0.028
CLAYSTONE	0.177	0.242	0.0	0.581
COAL	0.251	0.174	0.575	0.0

$\chi^2_{(8)}$ = 224.3 (Significant at +99.99% confidence level)

DIFFERENCE MATRIX

CONGLOMERATE	0.0	0.411	-0.093	-0.318
SANDSTONE	0.139	0.0	0.166	-0.305
CLAYSTONE	-0.102	-0.091	0.0	0.193
COAL	0.000	-0.126	0.124	0.0

4.2 the majority of bores have a fining-upwards transition path, with approximately a third of the bores having a dominant oscillating path in the coarse clastic phase. Indeterminate paths were obtained in a few bores. The bores showing a fining-upwards sequence are fairly evenly divided as to the presence of coal-claystone oscillations or coal-clastic transitions (i.e. reversion to a new fining-upwards cycle). However 77% of the matrices with the oscillating clastic lithology dominant contain dominant coal-claystone oscillations.

The majority of bores tend to oscillate in the coal-claystone mode, but these are evenly associated with fining-upwards transitions and conglomerate-sandstone oscillations. The coal-coarse clastic transitions, reflecting the weighting of the above groups, are usually associated with a fining-upwards cycle in the matrix.

From the pairing with the peat stage phases, it is evident that an oscillating clastic sequence is usually followed by an oscillating coal-claystone sequence; a coal-conglomerate transition is usually followed by a fining-upwards cycle rather than a conglomerate-sandstone oscillation. The converse of these two statements is not necessarily so, with the probabilities being fairly evenly distributed.

The difference matrices of the summed bores in each of the four groups in Table 4.2 are given in Table 4.3. The particular transition path in each group is reinforced over and above the path obtained for the sum of all bores (Table

Stage	Most Probable Transition Mode	% Bores in Each Group	Coal-Coarse Clastics	Coal-Claystone Oscillations
Clastic	Fining-upwards	60%	54.5%	45.5%
	Oscillating	36%	23%	77%
	Indeterminate paths	4%		
			Fining-upwards	Oscillating
Peat	Coal → Coarse Clastics	35%	80%	20%
	Coal-Claystone Oscillations	63%	50%	50%
	Indeterminate paths	2%		

<u>TABLE 4.2</u> Showing most probable transition path distribution for individual bores to show relationships between different stages of the transition path.

1. <u>CLASTIC (FINING-UPWARDS)</u>

	CONGLOMERATE	SANDSTONE	CLAYSTONE	COAL
CONGLOMERATE	0.0	0.426	-0.105	-0.321
SANDSTONE	0.018	0.0	0.284	-0.302
CLAYSTONE	-0.070	-0.078	0.0	0.148
COAL	0.022	-0.111	0.089	0.0

2. <u>CLASTIC (OSCILLATING)</u>

CONGLOMERATE	0.0	0.417	-0.101	-0.316
SANDSTONE	0.279	0.0	0.027	-0.305
CLAYSTONE	-0.147	-0.143	0.0	0.290
COAL	-0.027	-0.149	0.175	0.0

3. <u>PEAT (COAL COARSE→CLASTICS)</u>

CONGLOMERATE	0.0	0.341	-0.021	-0.320
SANDSTONE	0.054	0.0	0.227	-0.281
CLAYSTONE	-0.091	-0.053	0.0	0.144
COAL	0.104	-0.078	-0.026	0.0

4. <u>PEAT (COAL↔CLAYSTONE)</u>

CONGLOMERATE	0.0	0.465	-0.147	-0.318
SANDSTONE	0.172	0.0	0.145	-0.317
CLAYSTONE	-0.106	-0.127	0.0	0.233
COAL	-0.053	-0.152	0.205	0.0

<u>TABLE 4.3</u> Difference matrices for bores grouped according to most probable transition mode according to Table 4.2. All transition matrices are significant at +99.99% confidence level.

4.1).

No final assessment of any relation between basin structure and transition path mode can be made at this stage. However, it appears that the bores with oscillating clastic transitions tend to occur along the structure-high region to the west of the Macquarie Syncline, suggesting that here the number of coal-claystone transitions should also be higher. This is confirmed by visual examination of detailed seam sections in this area where the coals are generally of a highly banded nature, with most economic coal mining operations being located along the axis of the controlling Macquarie Syncline.

4.4 COAL CYCLES AND FINING-UPWARDS CYCLES

A further approach to the analysis of the sedimentary succession involves the recognition of fining-upwards cycles and coal cycles based on some ideal complete cycle within a given sequence. This method has been used by Read and Dean (1967, 1968) in studies on coal measure sequences in Scotland, as well as by Duff (1967), who carried out the only other similar study on data from the Sydney Basin. For comparison this technique was employed on the M.I.B. data.

An inherent problem with this approach is the difficulty of cycle definition and the dependence of the results and their interpretation on the criteria adopted. In the M.I.B. an "ideal" (Duff and Walton, 1962, and Duff, 1967) sequence would appear to be:-

Claystone)
)   Intra-seam oscillations only
Coal   )

Claystone

Sandstone

Conglomerate

This is essentially a fining-upwards cycle. In addition to fining-upwards cycles, coal defined cycles were counted using criteria as similar as possible to Duff (1967), (the differences being an attempt to filter out minor lithological variations). One reason for this was to determine if Duff's use of the presence of coal seams to define his cycles was suitable in the context of the M.I.B. succession. This was felt desirable because rather similar cherty claystones are often found immediately above and below the coal units in the upper part of the Newcastle Coal Measures, suggesting that the choice of coal seams as marker horizons may be of doubtful significance in relation to any major *cyclic* event. As Duff points out, if cycles are defined on the basis of coal seams, cycles can be present within what are normally considered as single coal seams. While cyclicity is clearly an important element in the succession of rock types within most N.S.W. Permian coal seams, (Smyth, 1966; Smyth and Cook, 1972) it is not clear that all the intra-seam cycles are similar in origin to what may be termed the larger scale cycles being discussed. In particular most coal/claystone alternations appear to be due to very minor fluctuations affecting the balance between peat growth and clastic accumulation. Since splitting of coal seams is not a common phenomenon in the M.I.B. the filtering of these oscillations seemed desirable. The problem of intra-seam coal-defined cycles was avoided by setting the minimum thickness at five feet (1.5 metres). Criteria for a fining-upwards cycle are that three of the units must be present and exceed the thicknesses in Table 4.4. This latter provision is to avoid defining cycles associated with relatively minor changes in sedimentation. Where an alternating sequence occurs which does not meet the requirements in Table 4.4 it is considered as part of one cycle and further units are added until these conditions are met.

4.4.1 Data Analysis (Cycles)

Data were collected over the interval of the M.I.B. from the logs of the bores shown in Fig. 4.1. The following variables were recorded:

a) Number of fining-upwards cycles.
b) Number of coal bearing cycles (i.e. coal defined cycles).
c) Total thickness in each bore.
d) Average fining cycle thickness in each bore.
e) Average coal cycle thickness in each bore.

To establish the relationships between the variables, least squares regression analysis, using first, second and third degree polynomials, was carried out on the pairs of variables

	Coal Bearing (Minimum Thickness 5 ft (1.5m)	Fining-upwards
Coal	0.2 ft (0.06m)	0.2 ft (0.06m)
Claystone	* 1 ft (0.3m)	1 ft (0.3m)
Sandstone	* 2 ft (0.6m)	5 ft (1.5m)
Conglomerate	* 5 ft (1.5m)	10 ft (3m)

*Minimum aggregate of 5 ft (1.5m) per cycle.

TABLE 4.4 Minimum thicknesses for the recognition of cycles.

Dependent variable	Independent variable	Correlation Coefficient (r)	Confidence Level on r	Gradient	95% Confidence Interval on gradient
No fining cycles	Total thickness	+0.54	>99.5%	+0.026	±0.012
(1) No. coal cycles	Total thickness	+0.56	>99.5%	+0.030	±0.014
(2) No. coal cycles	No. fining cycles	+0.49	>99.5%	+0.55	±0.30
(3) Average fining cycle thickness	Total thickness	+0.46	>99.5%	+0.10	±0.060
(4) Average coal cycle thickness	Total thickness	+0.15	80.90%	+0.048	±0.099
(5) Average fining cycle thickness	No. fining cycles	-0.48	>99.5%	-2.2	±1.2
(6) Average coal cycle thickness	No. coal cycles	-0.65	>99.5%	-4.0	±1.4
Data from Read and Dean (1967), Table 1 for comparison - the presumed equivalence to the M.I.B. correlation set is indicated by number in the left hand column.					
(1) No. complete cycles	Total thickness	+0.66	>99.5%		
(4) Av. cycle thickness	Total thickness	+0.63	>99.5%		
(6) Av. cycle thickness	No. complete cycles	-0.15	80-90%		

TABLE 4.5 Data from linear least squares best fit correlations for Moon Island Beach Subgroup data.

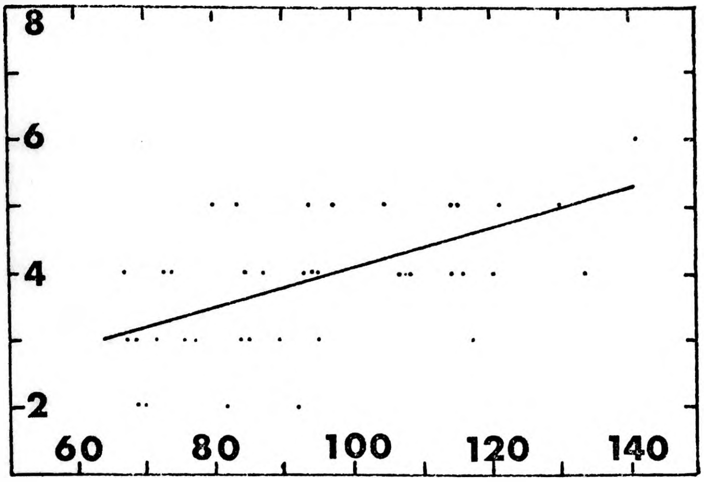
listed in Table 4.5. All relationships appear to be linear with the additional terms of the quadratic and cubic equations not being significant at normal confidence levels. Also in Table 4.5 are the calculated statistics and parameters of the linear regressions. The data are plotted in Figure 4.2.

The relation of the number of fining cycles versus the total thickness, and that of the number of coal cycles versus the total thickness shows a pronounced "basin pattern" (Read and Dean, 1967, 1968), i.e. as the thickness of the Sub-group increases the frequency of both fining-upwards cycles and coal cycles increases.

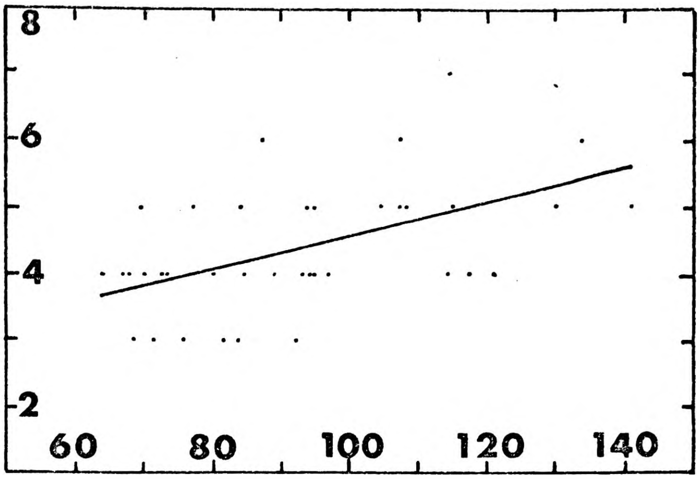
These results suggest that the number of both fining-upwards and coal cycles is directly related to variations in rates of subsidence of different areas within the basin.

The geological implications of the results of the analysis of the vertical variation are discussed subsequent to the presentation of the trend-surface analysis results.

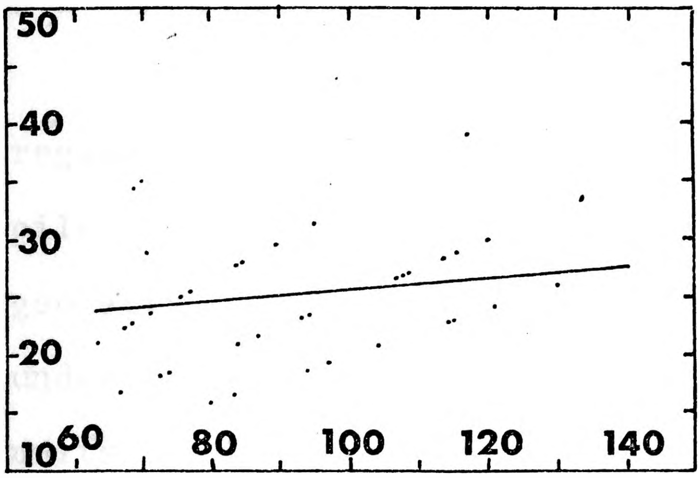
FIGURE 4.2 Linear regression plots of variables used in cycle analysis. Relevant statistics are given in Table 4.5



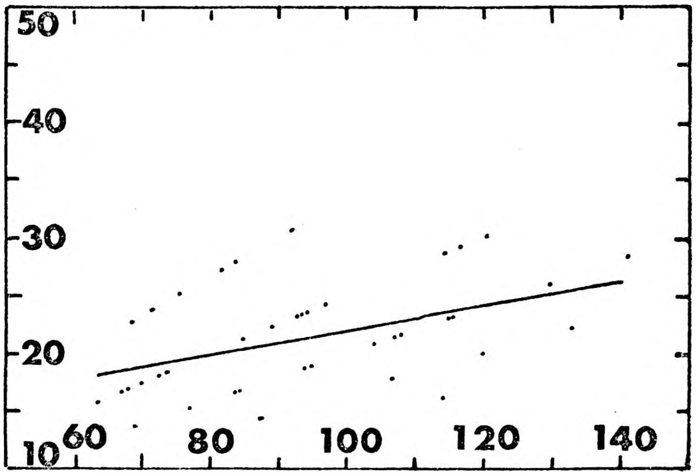
No. Coal Cycles vs Total Thickness(m)



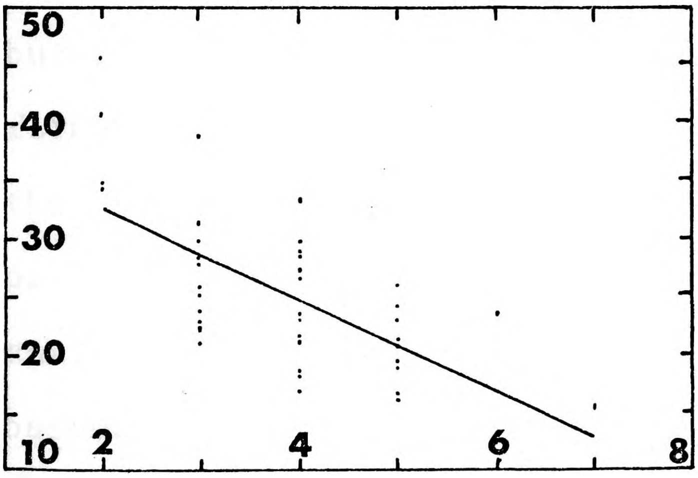
No. Fining Cycles vs Total Thickness



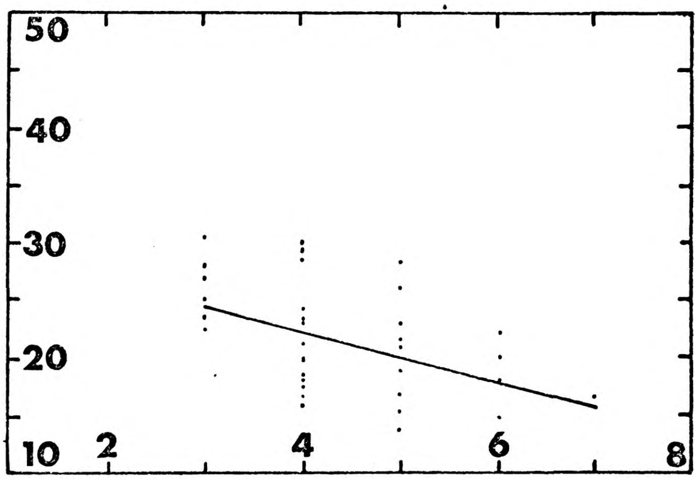
Mean Coal Cycle Thick. vs Total Thick.



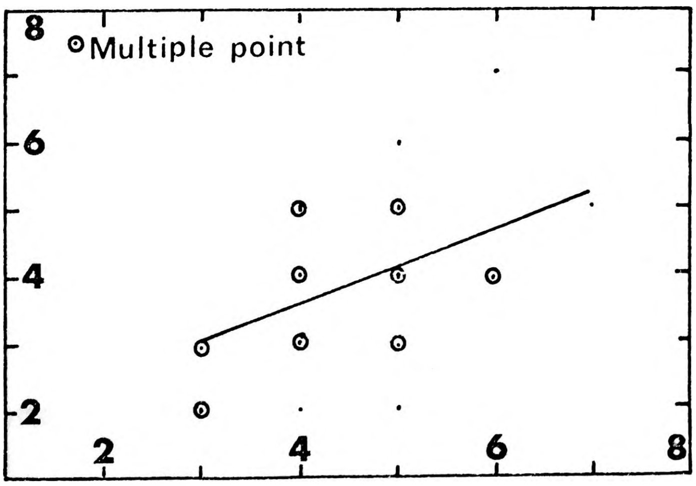
Mean Fining Cycle Thick. vs Total Thick.



Mean Coal Cycle Thick. vs No. Coal Cycles



Mean Fining Cycle Thick. vs No. Fining Cycles



No. Coal Cycles vs No. Fining Cycles

CHAPTER 5

ANALYSIS OF THE STRUCTURE AND THICKNESS VARIATIONS OF STRATIGRAPHIC UNITS OF THE MOON ISLAND BEACH SUB-GROUP

5.1 INTRODUCTION

In a study of the structural framework of a depositional regime where the continual accumulation of a sedimentary pile took place, the resolution of the elements of the geometry of each particular lithosome is important in understanding the causal relationships between successive units in that succession. The shape of a given body of rock is a product not only of the overall basement subsidence pattern but also of the shape and physical nature of preceding formations, the energy and depositional characteristics of the particular sediment, and the time over which the particular unit accumulated. Methods such as trend-surface analysis enable the recognition of the regional and local basement subsidence patterns and the detection of the ephemeral modifications to the subsidence pattern caused by individual formations. At any time within the basin the palaeotopography, which influenced drainage patterns and hence sedimentation, was the combined result of the temporary subsidence (and non-subsidence) superimposed on a background of persistent tectonic basement subsidence. For example the differential basement subsidence may cause an areal bias in stream and channel loci which may be modified by localised areas having slightly slower or faster rates of subsidence due to differential compaction of the underlying strata.

The aim in this section is to

i) isolate and identify *persistent* contemporary structures from the minor subsidence modifications classed here as *ephemeral* structures;

ii) to analyse the present-day structure of the area into components which can be related to the Permian subsidence patterns both at a regional and local scale, and features that result from subsequent deformations unrelated to any Permo-Triassic structure associated with the evolution of the Sydney Basin.

5.2 NOTE ON THE PRESENTATION OF RESULTS OF TREND-SURFACE ANALYSES

One of the problems (or advantages) of trend-surface analysis is the quantity of results derived. In the study twenty-eight separate variables were analysed, i.e. fourteen for each structure and thickness variable through trend-surfaces degree 1-4, giving a total of 112 trend-surface maps and 112 residual maps. For the sake of simplicity only the maps considered to be of geological interest are given here and discussed in detail. The statistics of the trend-surface analyses are tabulated in summary form. The sequence of the presentation of results is as follows.

Unit	No. Data Pnts	Coefficient of Determination Absolute F-ratio F-ratio (added terms) THICKNESS				STRUCTURE			
		1	2	3	4	1	2	3	4
Vales Pt Coal Member	39	0.03 0.52	0.17 1.36	0.42 2.39" 3.12"	0.44 1.42 0.23	0.51 23.4"	0.63 14.6" 7.3"	0.82 20.3" 14.2"	0.88 17.6" 3.8"
Karignan Conglom. Member	47	0.08 2.00	0.22 2.32' 2.36'	0.24 1.30 0.24	0.54 2.73" 4.15"	0.81 222.4"	0.93 285.4" 92.1"	0.96 295.0" 27.5"	0.98 312.2" 15.9"
Wallarah Coal	103	0.27 18.6"	0.37 11.5" 5.21"	0.48 9.6" 4.85"	0.66 12.11" 9.0"	0.81 215.6"	0.93 277.4" 92.6"	0.96 284.0" 27.2"	0.98 307.0" 16.8
Mannering Park Clayst.Mb	98	0.14 7.69"	0.17 3.81" 1.18	0.20 2.45" 0.78	0.24 1.84" 0.80	0.80 197.4"	0.94 283.0" 103.5"	0.96 270.6" 22.9"	0.98 272.0" 13.7"
Toukley Coal Lens	41	0.16 3.71"	0.19 1.68 0.42	0.25 1.16 0.59	0.55 2.34" 3.58"	0.32 9.2"	0.65 13.6" 17.4"	0.81 15.1" 8.7"	0.88 14.2" 4.0"
Buff Pt Coal Lens	40	0.11 1.81	0.22 1.58 0.13	0.35 1.24 1.81	0.47 1.01 0.68	0.54 17.5"	0.84 25.0" 25.1"	0.91 28.3" 1.3	0.93 16.6" 0.65

TABLE 5.1 Regression statistics for trend-surface analyses

Unit	No. Data Pnts	Coefficient of Determination Absolute F-ratio F-ratio (added terms)							
		THICKNESS				STRUCTURE			
		1	2	3	4	1	2	3	4
Teralba Conglom. Member	100	0.18 10.6"	0.40 12.8" 11.8"	0.43 9.16" 3.12"	0.54 7.26" 2.43"	0.83 244.5"	0.93 249.6" 66.4"	0.96 291.1" 35.7"	0.98 261.3" 10.4"
Claystone Roof of Grt.Nthrn	26	0.25 4.0"	0.31 1.85 0.31	0.40 1.26 0.63	0.44 0.67 0.15	0.71 29.0"	0.80 16.8" 4.9"	0.94 31.5" 14.4"	0.95 19.6" 1.1
Great Northern Coal	101	0.23 14.6"	0.30 8.16" 3.20"	0.49 9.78" 8.5"	0.60 9.18" 4.62"	0.83 240.8"	0.92 240.5" 64.2"	0.96 284.9" 35.8"	0.98 257.8" 10.5"
Eleebana Formation	103	0.22 14.0"	0.26 6.68" 1.58	0.35 5.54" 3.39"	0.39 3.95" 1.06	0.81 220.9"	0.92 234.9" 64.5"	0.96 256.9" 30.6"	0.97 204.4" 6.5"
Chain Valley Coal	77	0.05 1.46	0.06 0.88 0.11	0.13 1.13 1.41	0.16 0.87 0.48	0.85 216.0"	0.92 174.0" 33.9"	0.96 209.9" 27.5"	0.97 184.6" 7.3"
Claystone Base Chn. Val.Coal	77	0.08 3.37	0.14 2.39" 1.67	0.23 2.19" 1.83	0.41 3.01" 3.13"	0.84 207.8"	0.92 168.0" 33.7"	0.96 202.2" 27.0"	0.97 180.7" 7.6"

TABLE 5.1 Cont'd

Unit	No. Data Pnts	Coefficient of Determination Absolute F-ratio F-ratio (added terms)							
		THICKNESS				STRUCTURE			
		1	2	3	4	1	2	3	4
Doyalson Formation	76	0.27 13.37"	0.42 9.94" 5.8"	0.42 5.36" 0.40	0.51 4.53" 1.48	0.85 213.2"	0.92 157.7" 27.8"	0.96 201.1" 29.0"	0.98 224.2" 12.9"
(South) Fassifern Coal	101	0.06 2.90'	0.11 2.34" 1.90	0.19 1.37 0.27	0.23 1.87 2.51"	0.83 238.8"	0.92 211.0" 50.8"	0.96 234.0" 30.4"	0.97 182.6" 5.9"

' Significant at 95% confidence level

" Significant at 99% confidence level

TABLE 5.1 Cont'd

(i) Structure Variations: Trend-surfaces and residuals discussed for units at the base, middle and top of the M.I.B.

(ii) Thickness Variations: Trend-surfaces and residuals are discussed for all units.

The relevant statistics of all the trend-surface regression analyses are given separately in Table 5.1. F-ratios are given for the total and added terms and their significance, based on a 95% or 99% confidence levels are noted accordingly. The proportion of the total variation explained by the trend-surface is given by the coefficient of determination (Section 3.3).

Production runs for the trend-surface analyses were performed on the structure and thickness data from punched card decks containing bore name, grid location, and thickness value and a reduced level for the base of the particular formation. Structure and thickness trends were generated in separate runs. Output obtained was a symbol contour plot of each trend-surface (Deg. 1-4) at a scale of 1 cm = 3.08 kms, regression statistics and printed and punched lists of residuals. From these decks a magnetic tape file was set up for each stratigraphic unit containing all the raw data and residual information for structure and thickness. The tape file was then used as the data source for generating all the machine contour plots in this section, as well as for carrying out the comparison tests. Trend maps presented are re-drafted from the original line printer output; machine contoured residual and match maps are at a scale of 1 cm to 1.54 kms.

5.3 TREND-SURFACE ANALYSIS: STRUCTURE

From Table 5.1 it can be seen that the proportion of variation explained by the structure trend surfaces (Deg. 1-4) is consistently high for all units analysed. The high level of statistical fit to the variation in the structure data (based on F-tests of all terms at a 99% confidence level) is a result of structure data being sampled from real, smooth, and geometrically simple surfaces where local serial auto-correlation is very high. Any geographic variation in the variance of the data is smooth and continuous. Thus successively higher degree surfaces are able to accommodate the residual variation in the added degrees of freedom in the higher degree trend-surface coefficients. During early stages of the present investigation very high degree surfaces (up to seventh degree) were fitted to the structure data. The added terms of the fifth and sixth degree surfaces significantly improved the fit over the lower degree surfaces (based on F-test of the added terms at a 99% confidence level), while the seventh degree terms failed to significantly reduce the variation in the residuals. While the high degree surfaces are statistically significant regression surfaces the detail of the trend-surfaces approach that of a total fit conventional contour surface. Such complex trend-surfaces are not particularly useful in the present context where the aim is to determine the *partial* trend-surfaces which can be interpreted as regional geological components of the variation in the data. Residuals from the very high degree surfaces account for less than 2% of the variation in the data and accordingly, local autocorrelation effects are almost entirely removed from the data. Hence no geological interpretation can be inferred as to local variation components in the data. For the above reasons it was decided that the fourth degree surface would be an adequate upper limit in attempting to establish regional trends and isolating local features in the data. The fifth and sixth degree trend-surfaces include all the regional as well as virtually all the non-random local variation in the data and constitute *total* trend-surfaces (e.g. Parsley, 1971) in reference to the discussion in Chapter 3.

Analysis of the structure of units of restricted geographic extent, generally with an elongate distribution along the Macquarie Syncline axis and confined to the central part of the area covered by the bores used in the study, yielded lower levels of fit with fewer data points than those units sampled over the entire area. However the trend-surfaces for the minor units still were statistically significant based on F-test of both the added and absolute terms at a 99% confidence level. The main cause of the lower proportion of the variation explained by the surfaces for the

Toukley and Buff Point Coal Lenses is probably the result of these minor units being confined to an area of relatively more complex structure which, in turn, is statistically resolved as an area of relatively high local variance in the structure data. The widespread units that extend to the far south where the structural surface is very smooth (i.e. an area of low residual variance) yield higher levels of fit largely as a result of the low contribution of the far southern area to the total sums of squares of the residuals. As pointed out in Section 3.3 it is the areal variation in the variance of the data which may lead to inconsistencies in the criteria for rejection and selection of trend-surfaces.

As there is little variation in the level of fit of structure trend-surfaces for the major units and only slight variations in the coefficients of each degree trend-surface from unit to unit, only the trend-surfaces and residuals of the three major coal seams are discussed. They are considered sufficiently representative of the structure variations through the sequence being placed at the base (Fassifern and South Fassifern Coal), the approximate middle (Great Northern Coal) and the top (Wallarah Coal) of the M.I.B.

The data for the structure of Toukley and Buff Point Coal Lenses, being of limited extent, do not represent an adequate sample of the regional structure of the Macquarie

Syncline in the area studied. The trend-surfaces for these units tend to be trends of local structure features (with respect to the widespread formations). Even though the trend-surfaces for the minor units slightly better accommodate the broad local features in the data than the surfaces for the widespread units, the level of fit in both cases is sufficiently high that the trend patterns of the higher degree surfaces for the minor units are very similar to the widespread unit trend-surfaces over the corresponding area. The lower degree surfaces (Deg. 1-2) for the minor units are influenced by an absence of sampling in the south and south-west of the area where the regional dip of the M.I.B. strata is to the south-west. The first degree surface for the Buff Point Coal Lens, which extends more to the south than the Toukley Coal Lens, has a westerly dip while the planar surface for Toukley Coal Lens dips south. The geometries of the low degree surfaces appear more to reflect local characteristics of their sampling area than reflect meaningful components of the regional structure at the scale considered in the present study.

For these reasons and because of the overall similarity of trend-surfaces for all units only the structure trends of the major coal seams are discussed and considered representive of the structural modifications through the sequence of the M.I.B.

Structure trend maps are all at the same scale and have a contour interval of 50m. Structure residuals are contoured at 25m intervals.

5.3.1 Fassifern Coal and South Fassifern Coal: Structure

Although the Fassifern Coal and the South Fassifern Coal are not completely stratigraphically equivalent (*vide* Section 2.4.2) the base of the formations is equivalent and has been analysed as such. For convenience of description the two formations are jointly referred to here as the (South) Fassifern Coal.

a) Trend-Surfaces (Fig. 5.1)

Trend-surfaces (Deg. 1-4) were all statistically significant, based on an F-test at a 99% confidence level of all the regression terms; the added terms of each higher degree trend also resulted in a statistically significant improvement of the fit, based on an F-test of the added terms (99% confidence level).

The first degree surface accounts for 84% of the variation and approximates the regional homoclinal dip to the southwest of this northeastern corner of the Sydney Basin. The planar trend-surface strikes N 40 W and dips to the southwest at a rate of 15 m per kilometre. The second degree surface, explaining 92% of the variation, is a modification of the first degree surface and includes a synclinal component with its axis plunging to the southwest. The synclinal component, a quadratic approximation of the Macquarie Syncline, is isolated

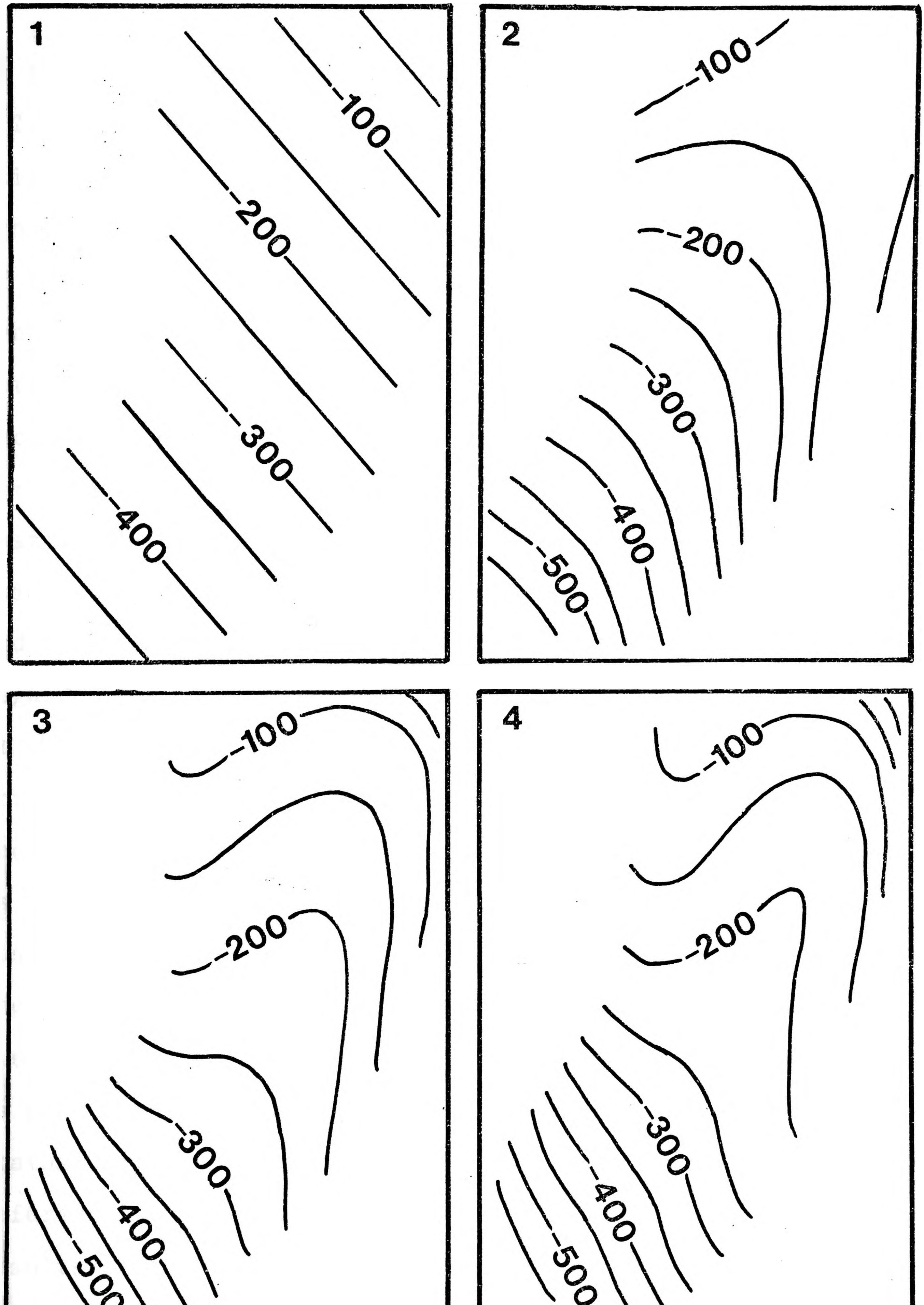


Fig. 5.1 (SOUTH) FASSIFERN COAL- Structure

Trend-surfaces Deg. 1- 4. (Scale: 1 cm = 3km) in the difference trend-surface (Degree 2-Degree 1) in Fig. 5.2 with a positive saddle zone across the northeast-southwest axis of the synclinal component. To the east and west of the syncline axis the positive saddle zone extends to the flanks of the syncline and the limbs become sub-parallel to the syncline axis. North and south along the axis, the difference surface is negative, expressing the synclinal troughs of the Macquarie Syncline. The saddle feature is a reflection of the Morisset Anticline which flanks the Macquarie Syncline to the west in the northern half of the area and of the rise in the axial zone of the Macquarie Syncline extending through Wyee and Norah Head on the coast. The rise across the axis may be regarded as a southeast attenuation of the Morisset Anticline.* It is termed here as the Wyee Saddle. The trough to the northeast of the Wyee Saddle coincides approximately with the southern part of Lake Macquarie and is referred to here as the Chain Valley Depression. The structural rise to the east of the Chain Valley Depression is termed the Swansea Rise. The area to the south of the Wyee Saddle which dips evenly to the southwest is termed as the Wyong Slope. This nomenclature is not intended to have any formal structural-stratigraphic status: it is introduced here solely for the convenient reference to persistent features which are present in the results of the trend-surface analysis of both structure and thickness.

The third and fourth degree trend-surfaces further

* See Fig. 6.1. A copy of Fig. 6.1 is included at the back of this volume.

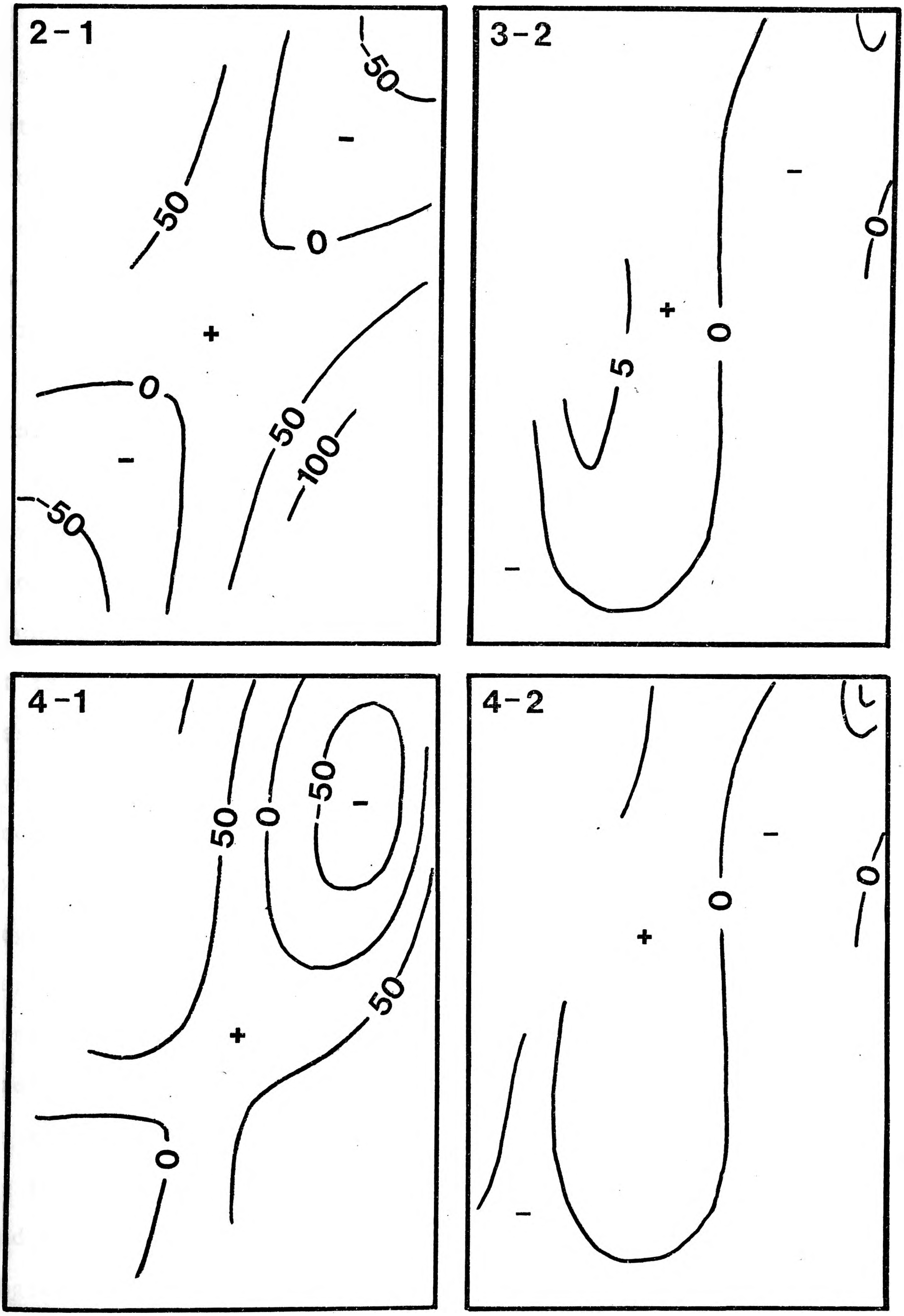


Fig. 5.2 Difference Trend-surfaces -(South)

Fassifern Coal Structure

resolve the structure with the spur-like ridge of the Morisset Anticline being expressed. While the fourth degree surface provides a statistically significant improvement (at a 99% confidence level), the geometric modification to the surface is slight. For this reason the residuals are presented only for the Degree 1-3 surfaces.

From the higher degree trend-surfaces it can be seen that the synclinal structural component is largely confined to the northern part of the area. The difference trend-surface between the Degree 3 and Degree 2 surfaces (Fig. 5.2) isolates the third degree component as a broad positive north trending ridge extending south along the Morisset Anticline; it is flanked to the east by a negative area which is a residual part of the synclinal pattern of the Macquarie Syncline. Most of the synclinal variation reports as the second degree trend. This observation is further evidenced by the difference surface for the Degree 4-Degree 1, and the Degree 4-Degree 2. The difference trend-surface for Degree 4-Degree 1 isolates the second, third and fourth degree components and includes the main structural elements of the area. To the northeast, centred over the Macquarie Syncline, is the Chain Valley Depression which is flanked to the west by the Morisset Anticline, to the east by the Swansea Rise and to the southeast by Wyee Saddle. However with the Degree 4-Degree 2 difference trend-surface most of the variation of the dominant structural features is removed and the trends remaining (Degree 3 and 4 components only) are weak expressions of regional structure variation not accounted for by the Degree 1 and 2 trend-surfaces.

The Wyong Slope to the south of the Wyee Saddle is present in the trend-surfaces and the difference trend-surfaces as a feature of different overall structural character to the area north of the Wyee Saddle. The structure of the Wyong Slope is only a very slightly flexured, but more steeply dipping, surface. There is a distinct inflexion in the gradients across the Wyee Saddle between the 'folded' northern point of the area and the southern part which has a steeper homoclinal dip but a less marked fold component.

b) Residuals (Fig. 5.3a,b,c)

Negative residuals from the first degree structure trend-surface occur in two domains: one, in the north along the Macquarie Syncline and corresponding to the Chain Valley Depression, and the other to the far south over the Wyong Slope. The positive residual domains which flank the northern negative residual to the east and west correspond to the Swansea Rise and the Morisset Anticline. The Morisset Anticline extends to the south and attenuates across the Wyong Saddle, which isolates the two negative structural areas.

The sharp rise of the structure trend-surfaces and residuals along the coast, especially near Swansea, may indicate faulting along the eastern side of Lake Macquarie or perhaps reflect an uplift along the continental margin due

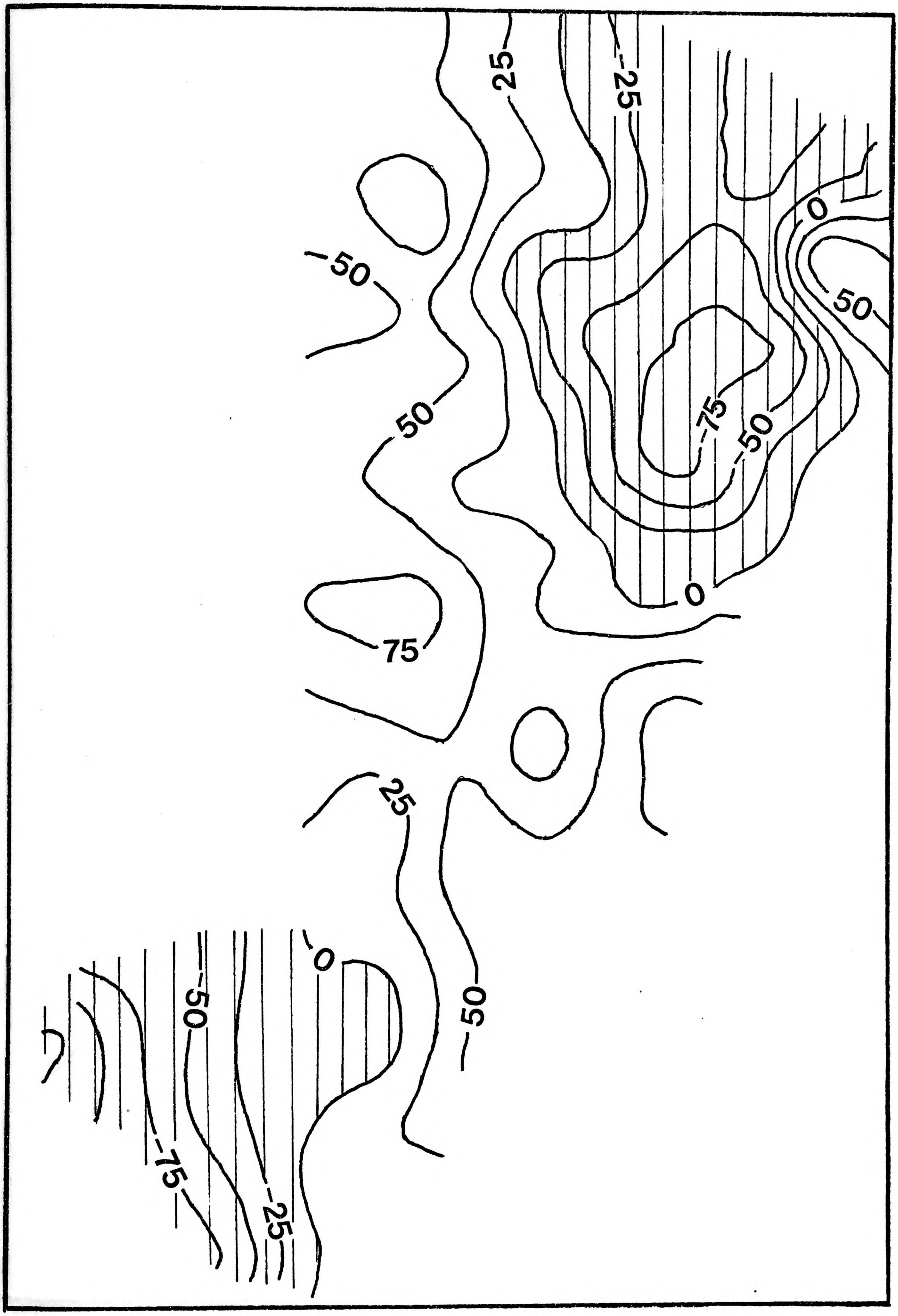


FIGURE 5.3a (South) Fassifern Coal - 1st Degree Structure Residuals (Scale: 1cm = 1.5km)

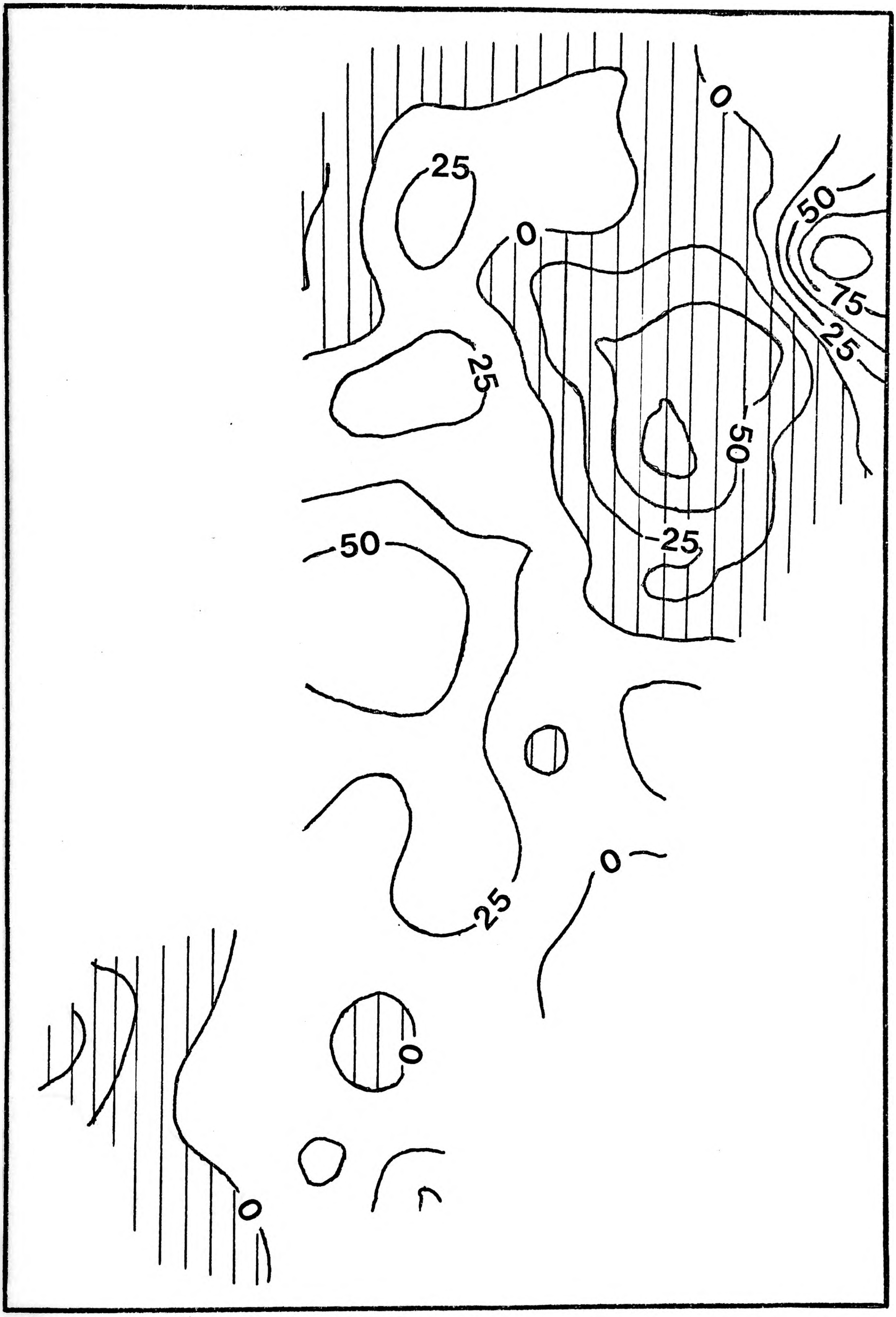


FIGURE 5.3b (South) Fassifern Coal - 2nd Degree Structure Residuals

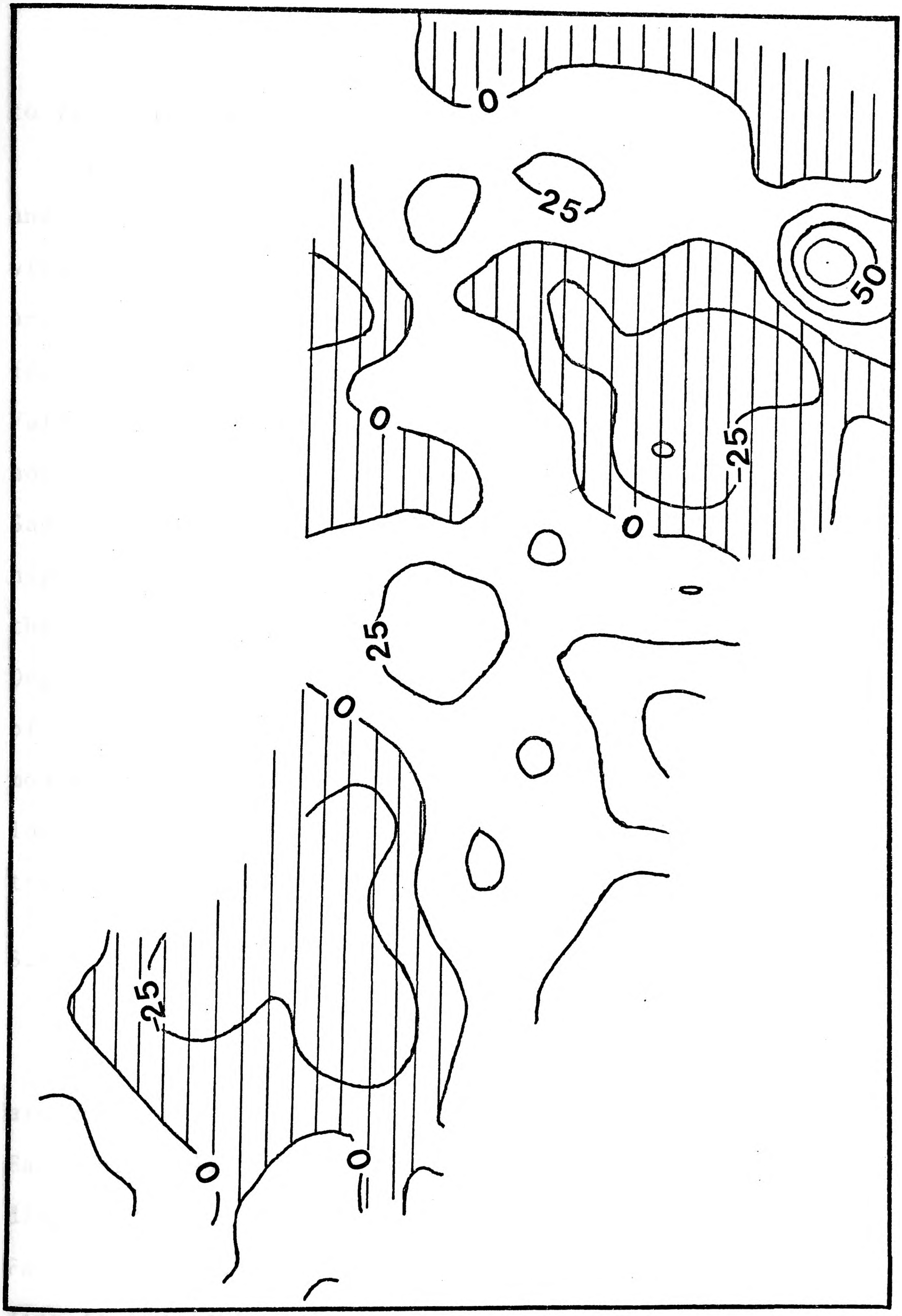


FIGURE 5.3c (South) Fassifern Coal - 3rd Degree Structure Residuals

to tightening at the margins of the Australian polygon.

The geographic extent and configuration of the positive and negative residual domains does not significantly change with increasing degree of trend-surface except that the amplitude of the residuals is generally lower. The major features present in the first degree trend (i.e. the Chain Valley Depression, and the Morisset Anticline) persist but are not as extreme as in the first degree residuals. The Wyee Saddle becomes less prominent but is still present in the higher degree residuals. Although the overall boundaries of the residual domains are very similar, especially for the Degree 1 and 2 residuals, the shapes of the residual domains of the Degree 3 trend-surface tend to become slightly modified to include or exclude adjacent areas which are of low amplitude (i.e. close to zero) residuals in the Degree 2 trend-surface residuals.

5.3.2 Great Northern Coal: Structure

a) Trend-Surfaces (Fig. 5.4)

The structure trend-surfaces for the Great Northern Coal are geometrically similar to those obtained for the (South) Fassifern Coal. The surfaces for the Great Northern Coal are displaced approximately 50 m above those for the (South) Fassifern Coal. The first degree surface strikes N 35 W and dips to the southwest at a rate of 15 m per kilometre. Higher degree surfaces increasingly accommodate the 'fold' components of the Macquarie Syncline.

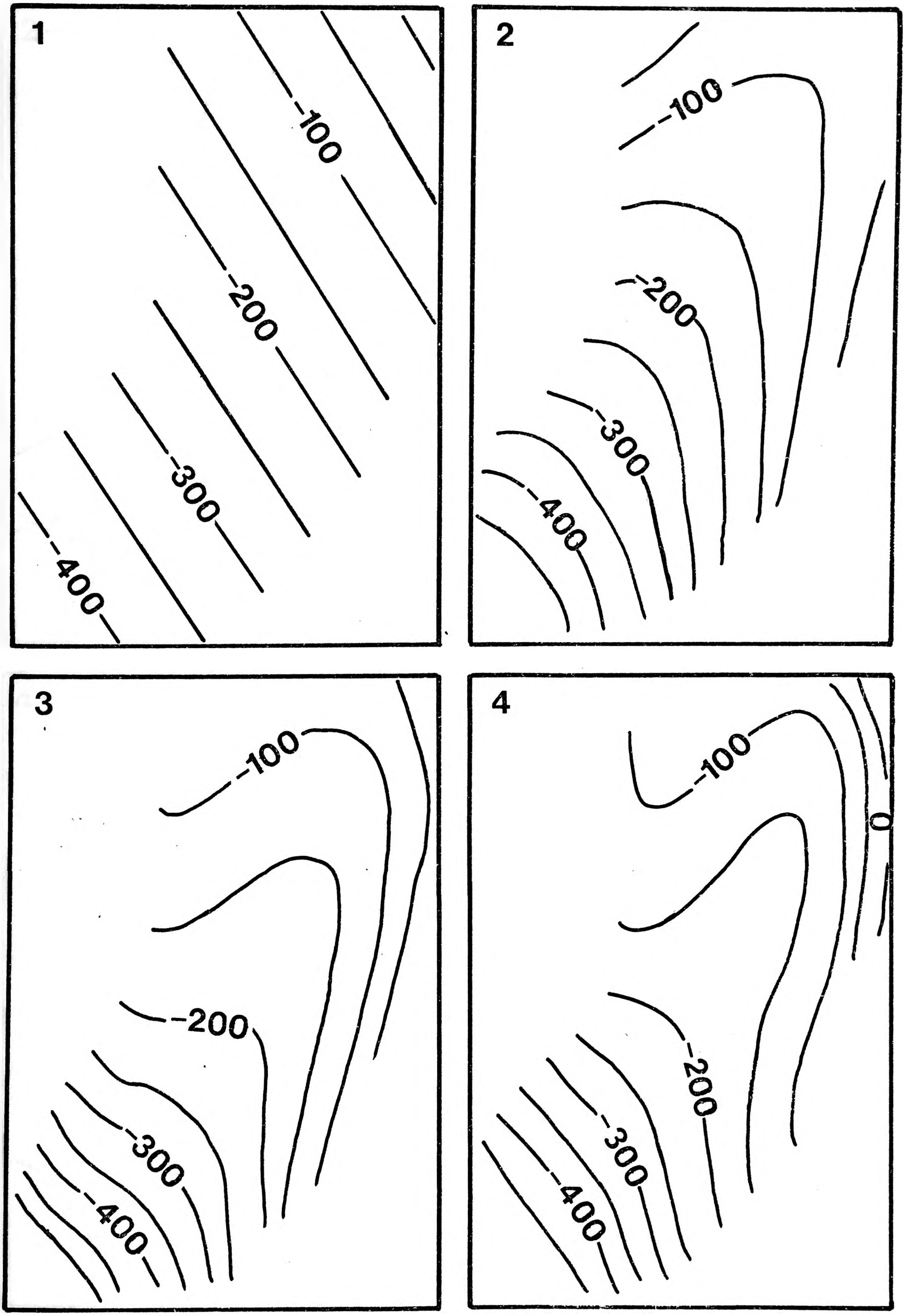


Fig. 5.4. GREAT NORTHERN COAL – Structure

Trend-surfaces Deg. 1–4

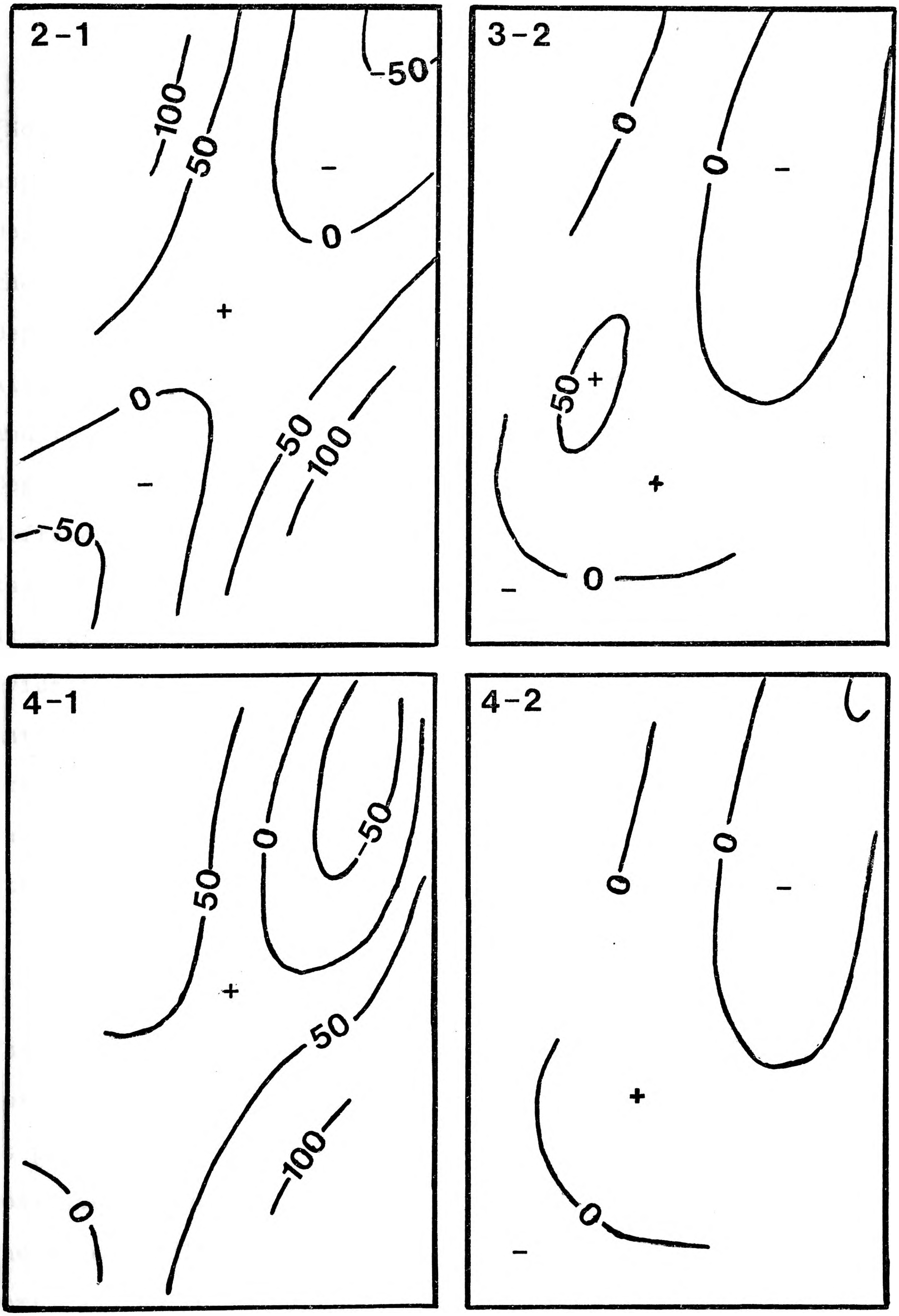


Fig. 5.5. Difference Trend-surfaces - Great Northern Coal Structure

The main changes between the trend-surfaces for the (South) Fassifern Coal and the Great Northern Coal are apparent in the difference trend-surfaces Fig. 5.5. For the Degree 2-Degree 1 and Degree 4-Degree 1, difference surfaces the Wyee Saddle persists and separates the Chain Valley Depression from the Wyong Slope to the south. However the higher degree components i.e. the pure third and the third and fourth degree coefficients which are mapped in the Degree 3-Degree 2, and Degree 4-Degree 2 surfaces are slightly different from those obtained for the (South) Fassifern in that the Chain Valley Depression is more strongly expressed as a closed negative feature. The Wyee Saddle is also more evident as a southeasterly extension of the Morisset Anticline. The changes in configurations of the differences trend-surfaces for the Great Northern Coal and the (South) Fassifern Coal are however, relatively slight and reflect minor structural differences between the two coal formations.

b) Residuals (Fig. 5.6a,b,c)

The first degree structure residuals for the Great Northern Coal are very similar in their geographic distribution to those for the (South) Fassifern Coal. The Chain Valley Depression is present and is separated from the Wyong Slope by the positive residual domain which represents the Wyee Saddle. The Wyee Saddle domain rises to the southeast and to the north and northwest along the Morisset Anticline. The Swansea Rise flanks the Chain Valley Depression to the east and roughly

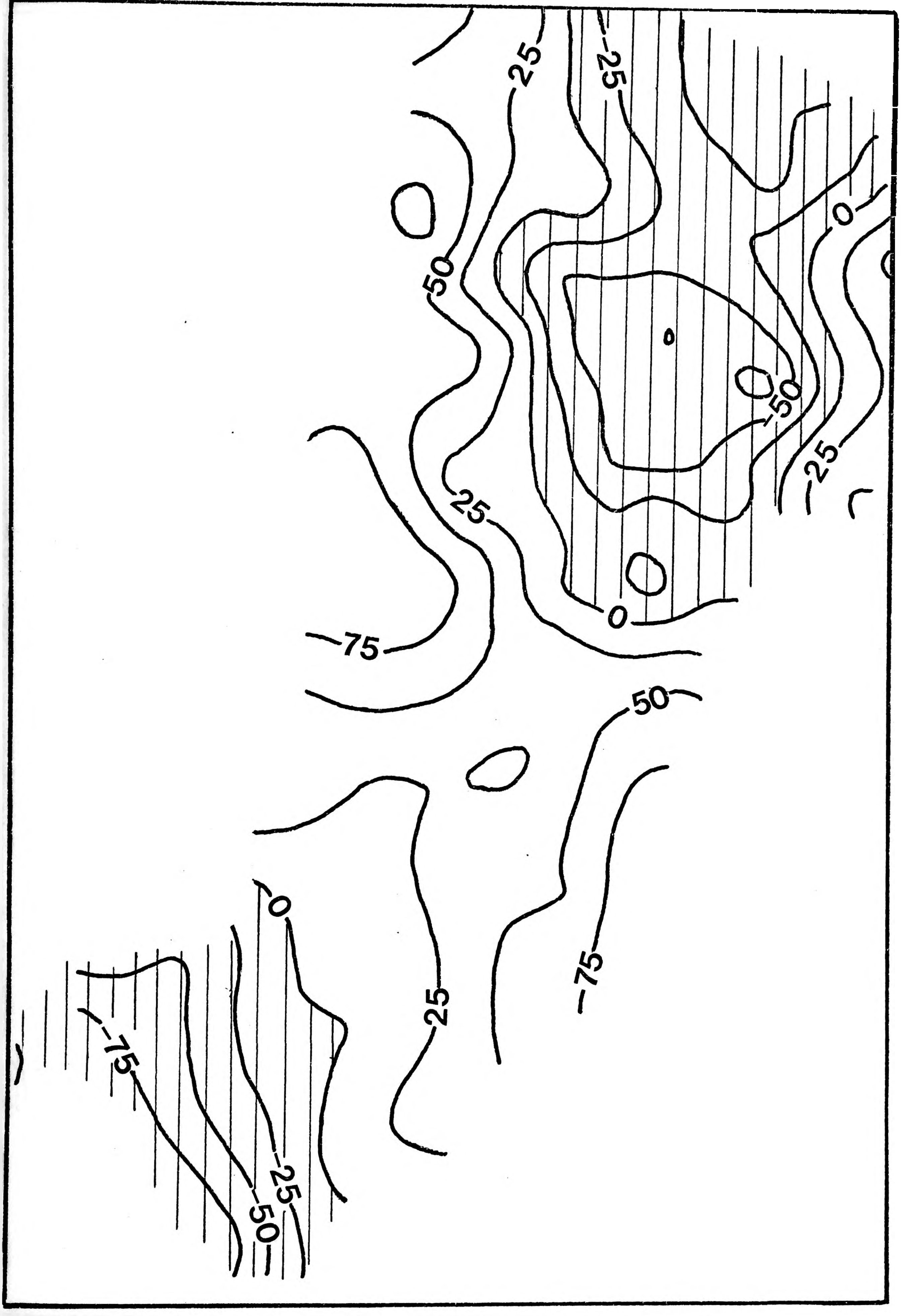


FIGURE 5.6a Great Northern Coal - 1st Degree Structure Residuals

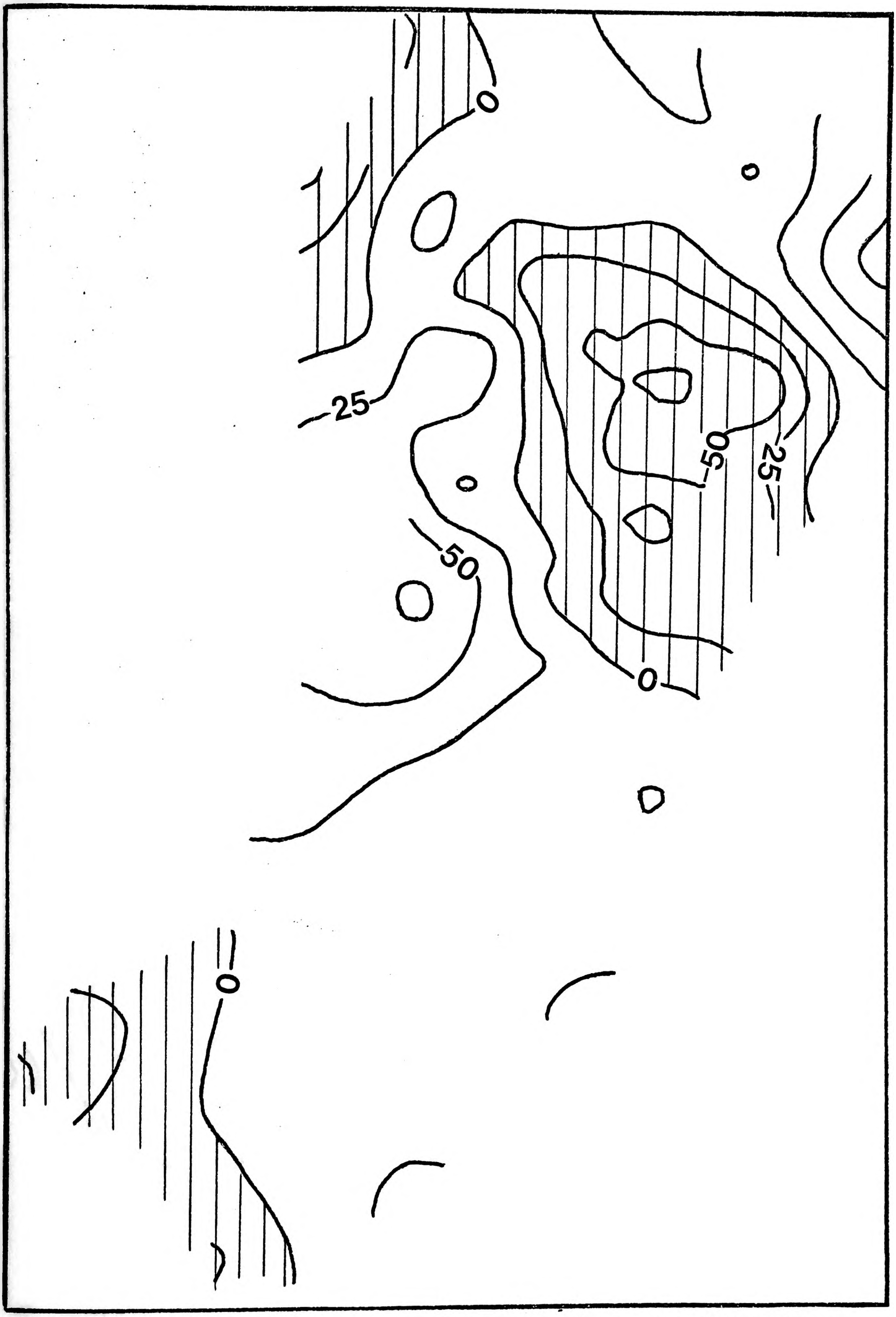


FIGURE 5.6b Great Northern Coal - 2nd Degree Structure Residuals

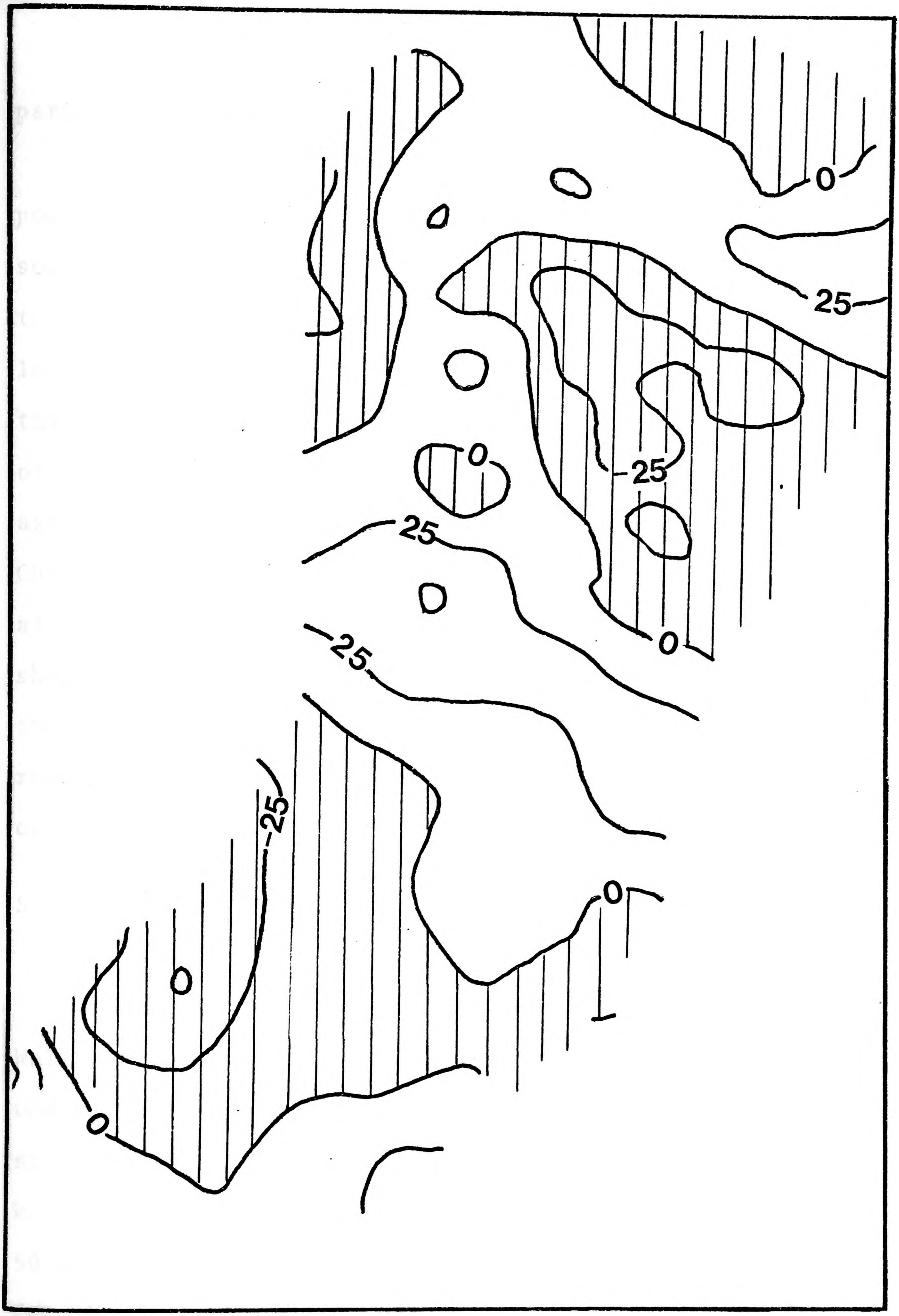


FIGURE 5.6c Great Northern Coal - 3rd Degree Structure Residuals

parallels the present coastline.

The second degree residuals reveal a broadening of the positive Wyee Saddle such that it occupies all but the extreme southwest of the southern part of the area encroaching into the Wyong Slope zone. The Chain Valley Depression is somewhat larger and slightly open to the southeast. Residuals from the third degree trend-surface which separately accommodate part of the Chain Valley Depression along the Macquarie Syncline axis, show a weakened negative domain over the area of the Chain Valley Depression but a more distinct positive domain along the northwest axis of the Wyee Saddle. Overall the shape and geographic extent of the domains has not changed from the underlying (South) Fassifern Coal even though some rapid variations in the thickness of the intervening strata occur.

5.3.3 Wallarah Coal

a) Trend-Surfaces (Fig. 5.7)

Generally the geometries of the trend-surfaces for the Wallarah Coal closely resembles those of the trends of the underlying units already discussed. The first degree trend strikes N 32 W and dips to the southwest at a rate of 16 m per kilometre and is displaced between 30 m (in the south) and 50 m (in the north) above the planar structure trend-surface for the Great Northern Coal. The variation in the displacement is a result of the thinning of the Teralba Conglomerate Member in the far south across the Wyong Slope. As before the higher

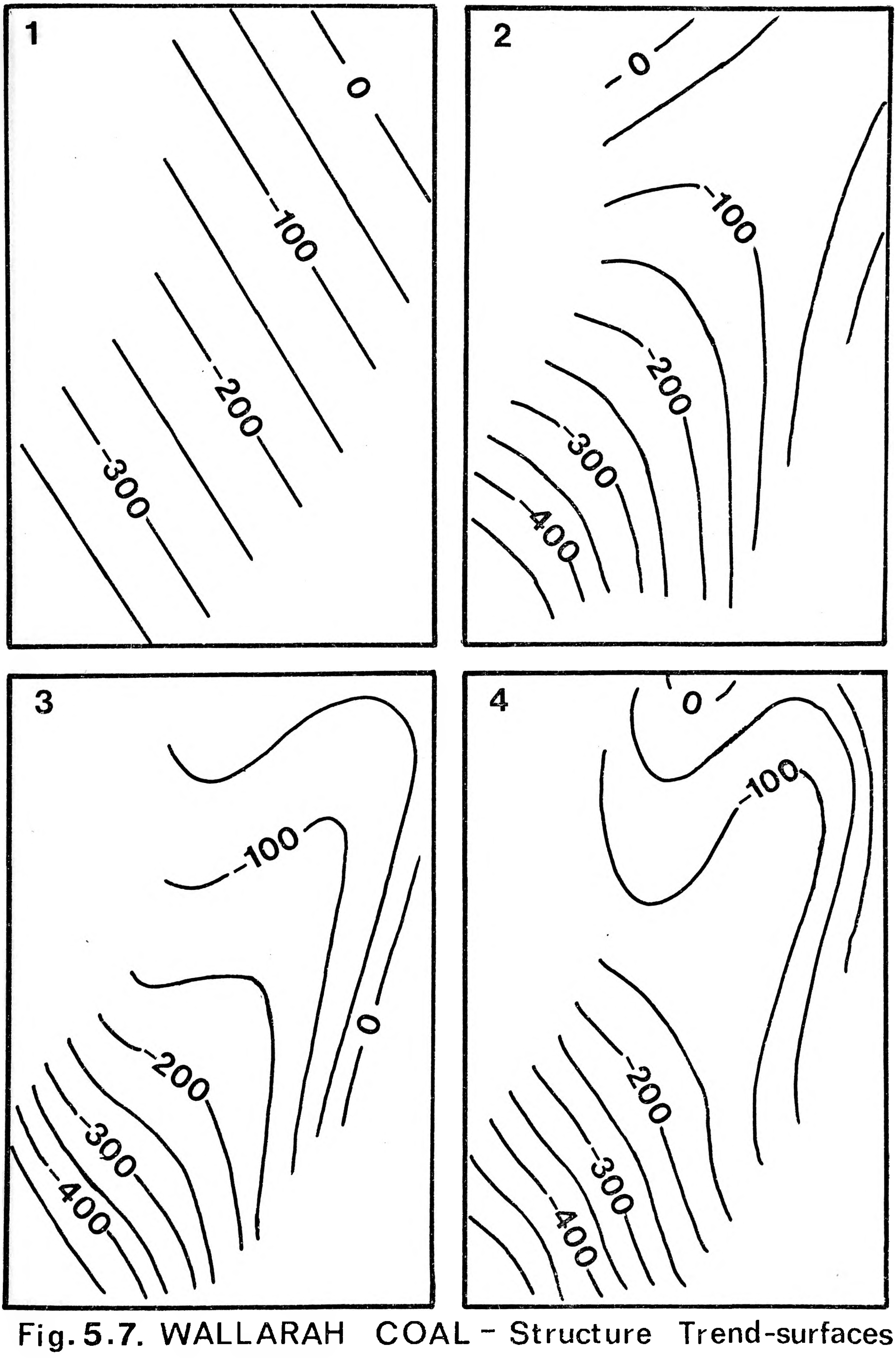


Fig. 5.7. WALLARAH COAL - Structure Trend-surfaces

Deg. 1-4

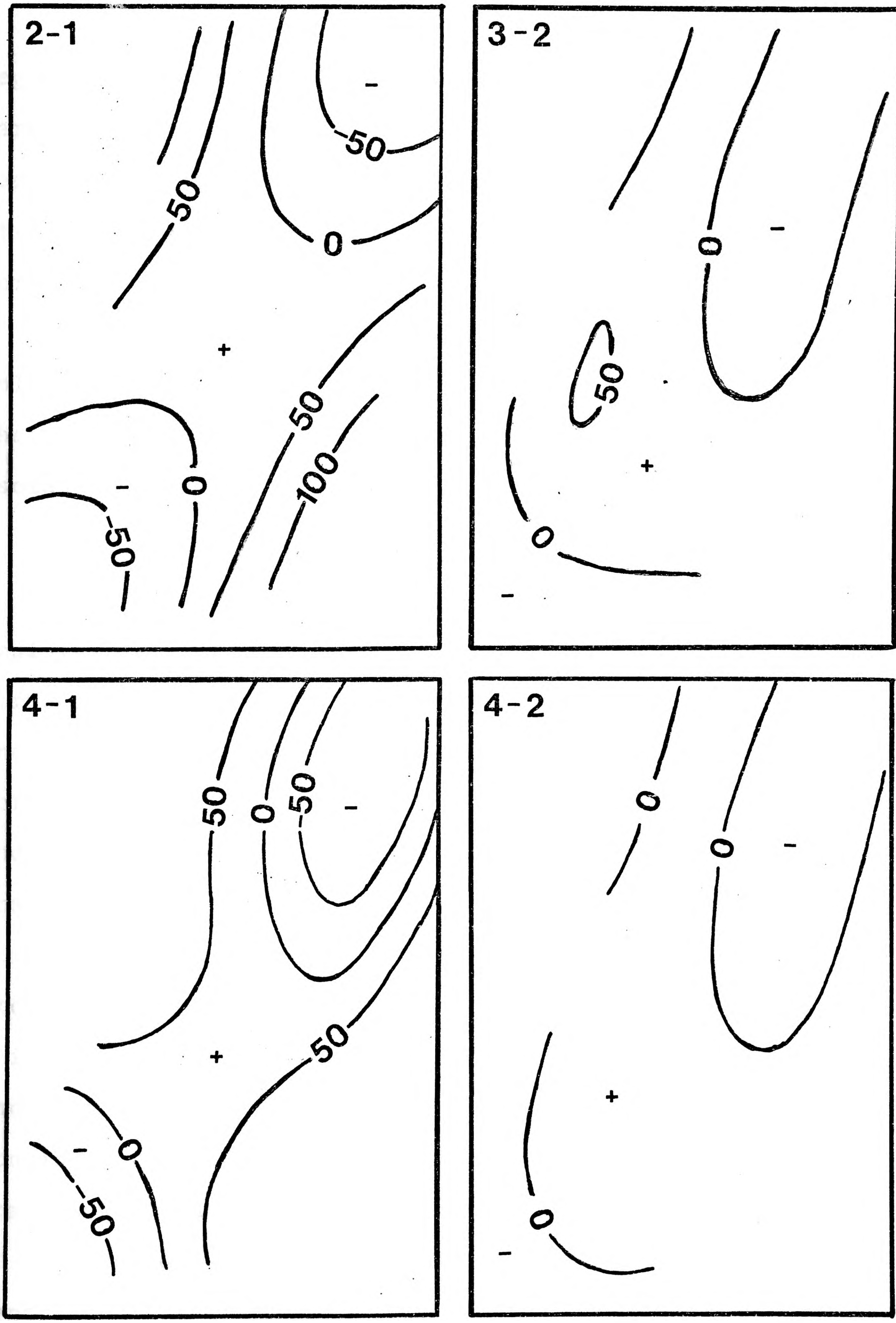


Fig. 5.8. Difference Trend-surfaces – Wallarah Coal Structure

degree trend-surfaces increasingly accounted for the synclinal variation component in the structure and the third and fourth degree trend-surfaces begin to reflect the prominent structural features of the Chain Valley Depression and the Morisset Anticline.

The difference trend-surfaces (Fig. 5.8) are again not unlike those obtained for the Great Northern Coal, with the Chain Valley Bay Depression and the Wyee Saddle being partly isolated as negative and positive features respectively.

b) Residuals (Fig. 5.9a,b,c)

The first degree structure residuals for the Wallarah Coal indicate an extended residual in the northern part which corresponds to the Chain Valley Depression and centred along the axis of the Macquarie Syncline. To the west and east the northern positive domain is flanked by the Morisset Anticline and the Swansea Rise respectively, while to the south the positive Wyee Saddle residual separates the other negative structure domain, the Wyong Slope. Part of the structural steepening in the Wyong Slope may be partly caused by the thinning of the Teralba Conglomerate Member over the Wyee Saddle although as noted the thinning of the Teralba Conglomerate Mb. has also affected the planar trend-surface for the Wallarah Coal.

The second degree residuals show a broadening of the central positive Wyee Saddle domain as compared with the domain defined by the first degree residuals but the northern negative

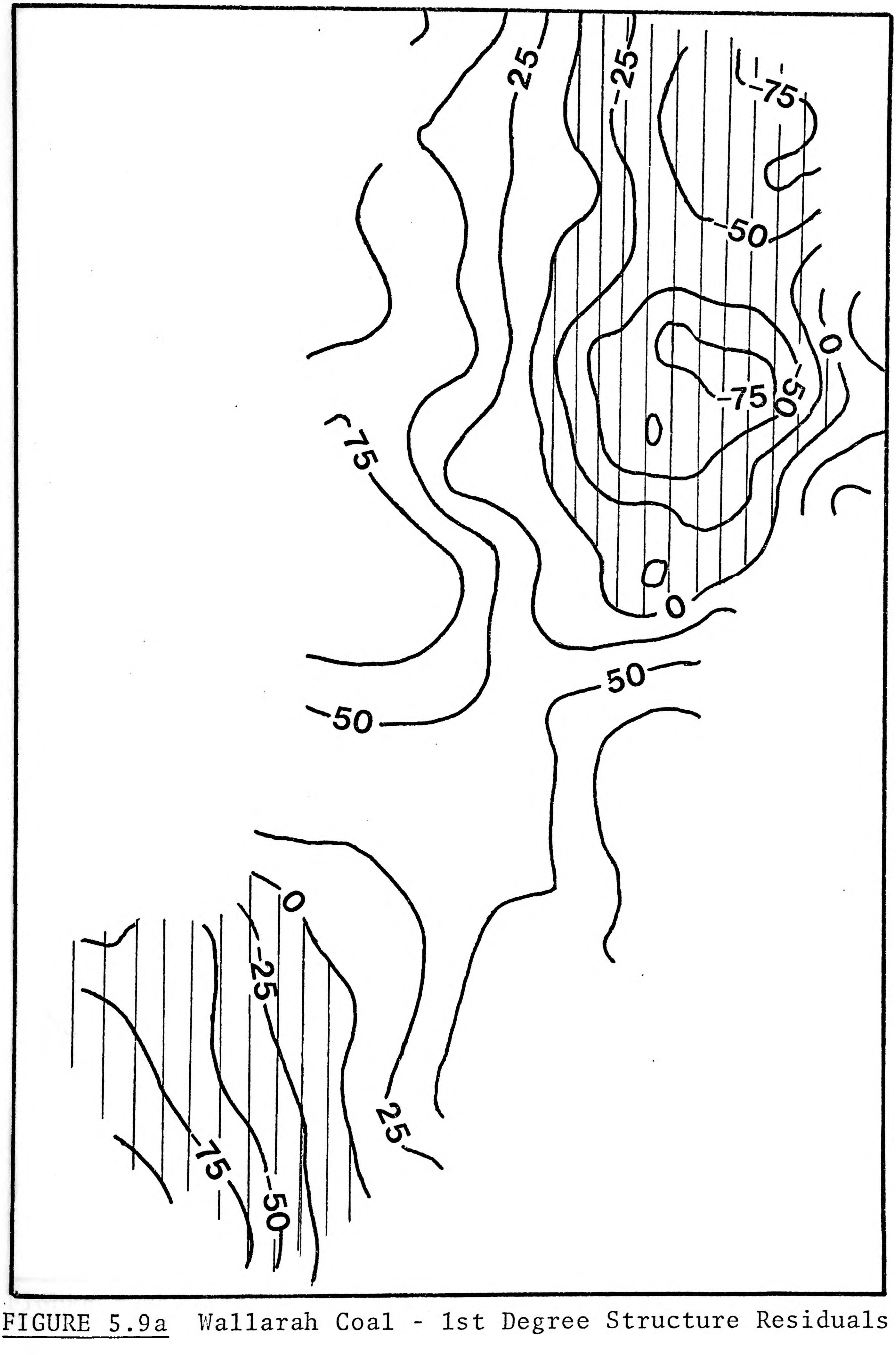


FIGURE 5.9a Wallarah Coal - 1st Degree Structure Residuals

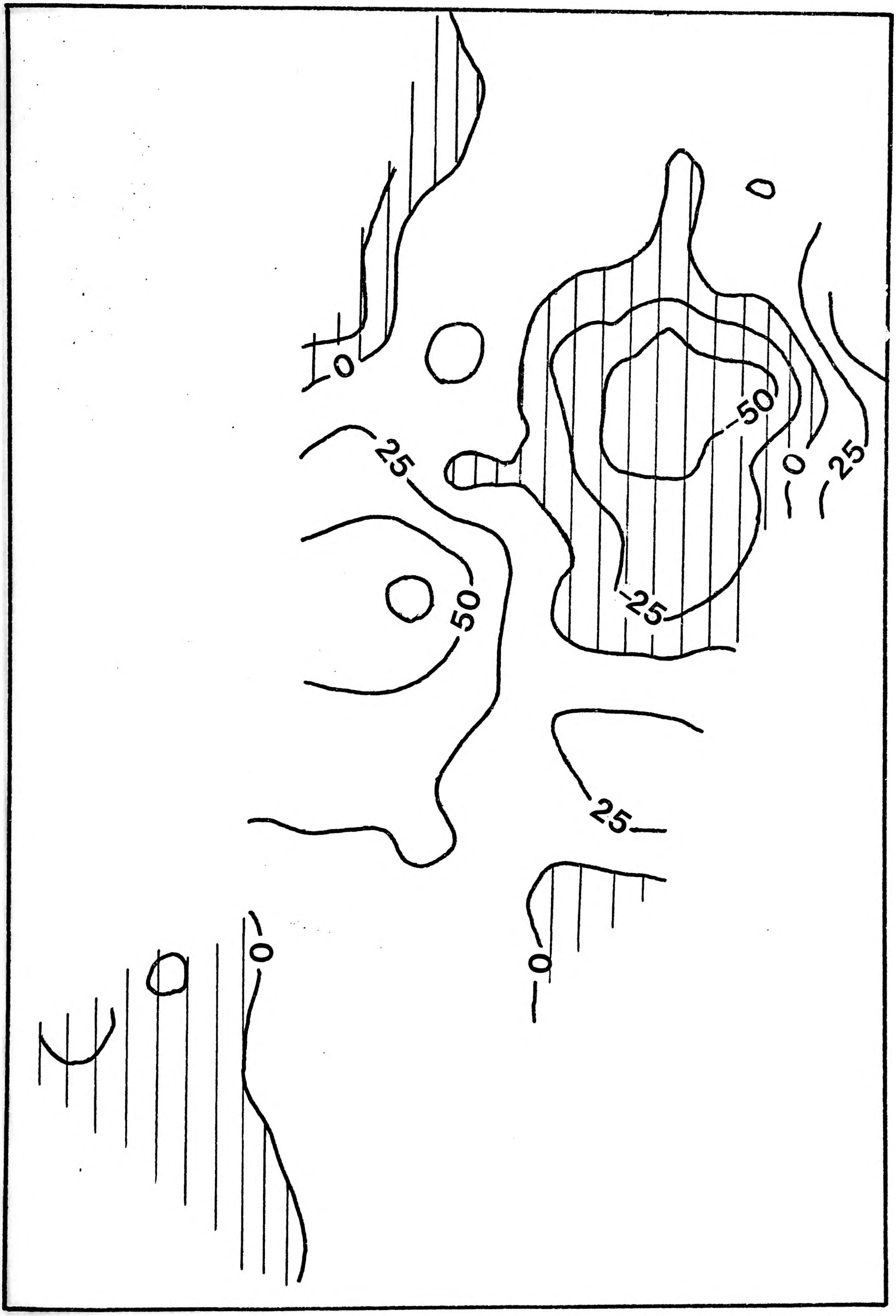


FIGURE 5.9b Wallarah Coal - 2nd Degree Structure Residuals

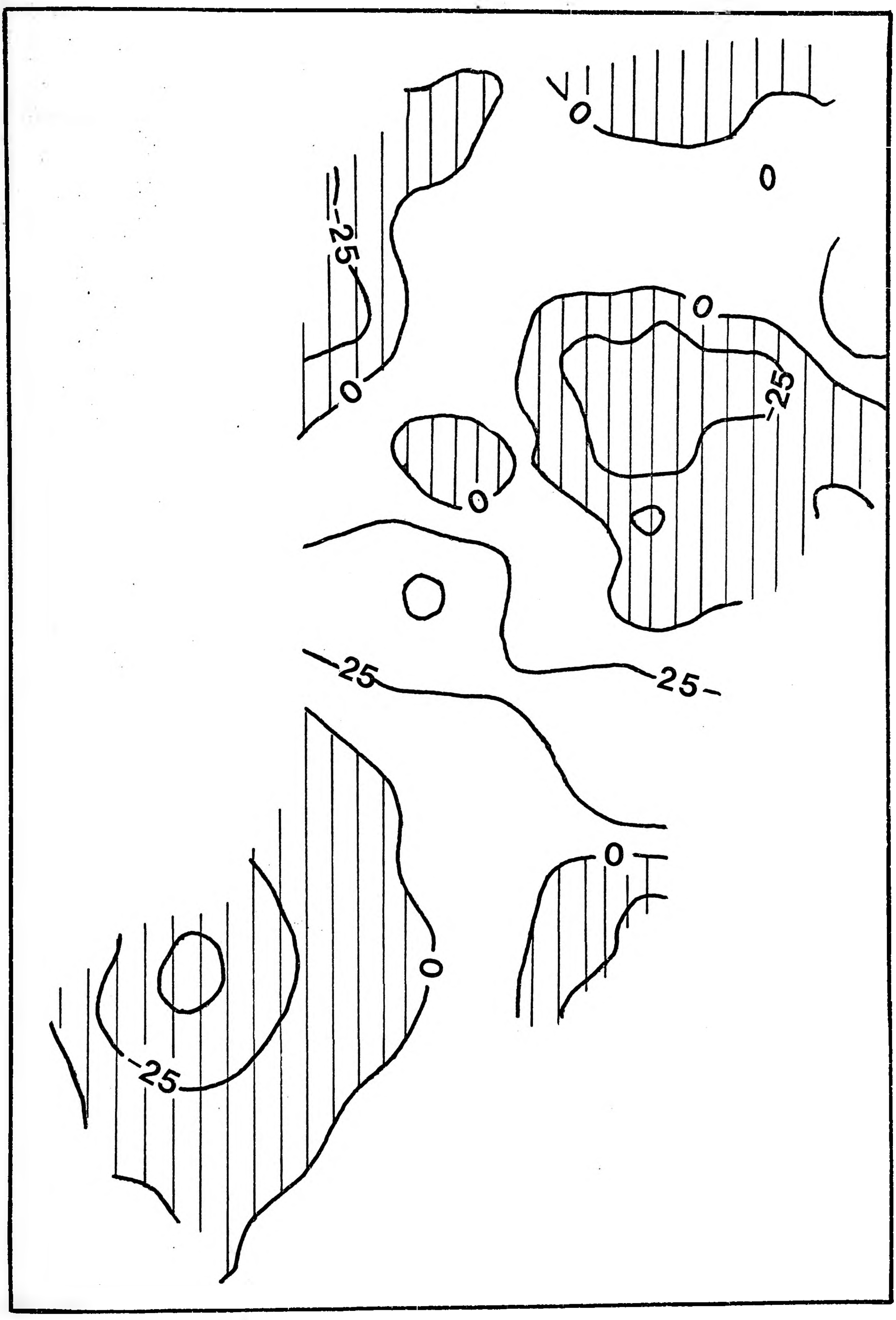


FIGURE 5.9c Wallarah Coal - 3rd Degree Structure Residuals

domain over the Chain Valley Depression persists.

Similar to the third degree structure residuals of Great Northern Coal, there is a general weakening of the amplitude of the third degree structure residuals for the Wallarah Coal which is accompanied by a more diffuse geographic pattern in the residual domains. However the main local structural elements described above are still present.

It is interesting to note that for all the widespread formations the proportion of variation accounted for by the trend-surfaces is particularly high. Accordingly the variation not explained, presented in the residual maps is relatively low. However while the proportion of the variation in the residuals is low they all reflect the existence of prominent local structural features which are superimposed on the regional structure of the area.

5.4 TREND-SURFACE ANALYSIS OF THICKNESS VARIABLES

5.4.1 Fassifern Coal-South Fassifern Coal: Thickness

As noted in Section 2.4.2 the Fassifern Coal has not been analysed separately. Thickness data of the Fassifern Coal have been analysed with the South Fassifern Coal. The data sets were amalgamated as it was considered that the data for the Fassifern Coal in the area studied were not of sufficient geographic extent to be reliably interpreted on a regional scale. Also as the plies at the top of the Fassifern Coal equivalent to the Chain Valley Coal would contribute only a

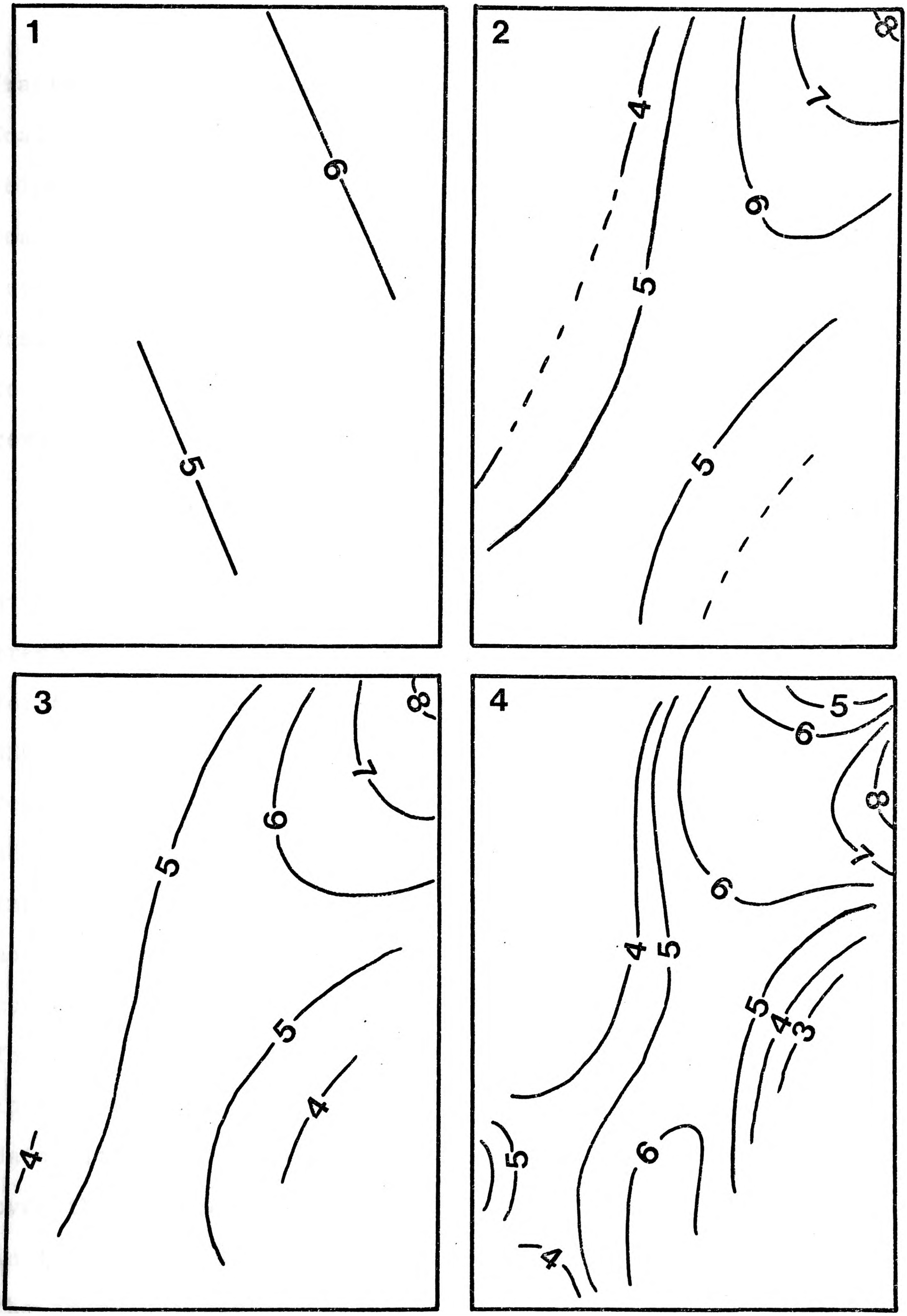


Fig.5.10 (SOUTH) FASSIFERN COAL- Thickness

Trend-surfaces Deg. 1-4

fraction (< 20%) to the total thickness of the Fassifern Coal, the effect of the additional plies should only slightly weight the trend-surfaces. However the contribution of these coal plies must still be taken into account when interpreting both the regional and local thickness variations of the South Fassifern Coal and the Fassifern Coal. Overall there appear to be no adverse effects on the trend-surface analysis as a result of considering the two formations as equivalent units.

a) Trend-Surfaces (Fig. 5.10)

Only the first and second degree surfaces are significant at the 95% confidence level based on the F-ratios of all the trend-surface coefficients. The first degree surface accounts for 6% of the total variation and is a plane dipping to the WSW and corresponds with a planar wedge of sediment (coal) regionally thickening to the ENE. Although the F-ratio of the additional terms of the second degree trend do not significantly improve the level of fit at a 95% confidence level, the absolute level of fit, based on the F-ratio of all the coefficients, is still significant at the 95% confidence level. The second degree surface, accounting for 11% of the variation, indicates a plunging antiform trend pattern in the thickness data with the axis of the antiform trending N 35 E and centred over the Macquarie Syncline. The planar component is manifest in the plunge element of the surface (i.e. a value of 8 m for the trend-surface in the north and 5-6 m in the south). The fold component is present as an increase in thickness from both the east and west in towards the axis of the antiform.

The third and fourth degree surfaces do not represent significant trends at the 95% confidence level (based on the F-test of all the coefficients); similarly the added terms do not significantly improve the fit over the lower degree surfaces. However although the third and fourth degree surfaces are not statistically significant at normal confidence levels they somewhat further resolve the thickness variation with the fourth degree surface including localised features in the data. The third degree surface, accounting for 12% of the variation is a antiform trend with curved axis deflecting to the northeast and coinciding with the Macquarie Syncline axis. The fourth degree surface accounting for 27% of the variation indicates the dominant antiform trend in the thickness of the South Fassifern Coal and the Fassifern Coal while superimposed on this trend are smaller zones of thickness trend extrema to the northeast and southwest. The additional thickness of coal at the top of the Fassifern Coal may partly contribute to the thickness trend maximum in the northeast but it does not appear to affect the regional antiform thickness trend. Furthermore while the planar thickness component may be influenced by the additional thickness of the coal plies equivalent to the Chain Valley Coal in the Fassifern Coal, the deterioration of the South Fassifern Coal in the far south and a general increase in thickness of the South Fassifern Coal to the north would seem to be the main control in the planar regional thickness variation.

In reference to the discussion in Chapter 3 on partial and total trend analysis it may be noted that each of the lower degree surface are components of the regional variation and the higher degree surfaces (Deg. 3-4) although not statistically significant on the basis of an F-test at normal confidence levels are still geologically useful. The low levels of fit obtained for all the trend surfaces (Deg. 1-4) may be a reflection of the high local variance which may exist for the South Fassifern Coal and the Fassifern Coal as a result of difficulties in defining a consistent basal marker horizon. The effect of the extraneous variation has not however been sufficient to distort the overall regional pattern of the thickness variation. The results obtained for the basal formation of the M.I.B. are consistent with the other widespread coals thereby, to some extent, empirically confirming the lack influence of local measurement difficulties on the trend-surfaces.

The difference trend-surface between the second and first degree surfaces is given in Fig. 5.11; the contour interval is 0.5 m to emphasise the variation of the surface. The antiform component of the second degree trend is isolated from the planar regional variation as a broad elongate positive ridge flanked to the east and west by negative areas and trending N 35 E along the Macquarie Syncline. The saddle point of this surface lies in the Toukley-Munmorah area and

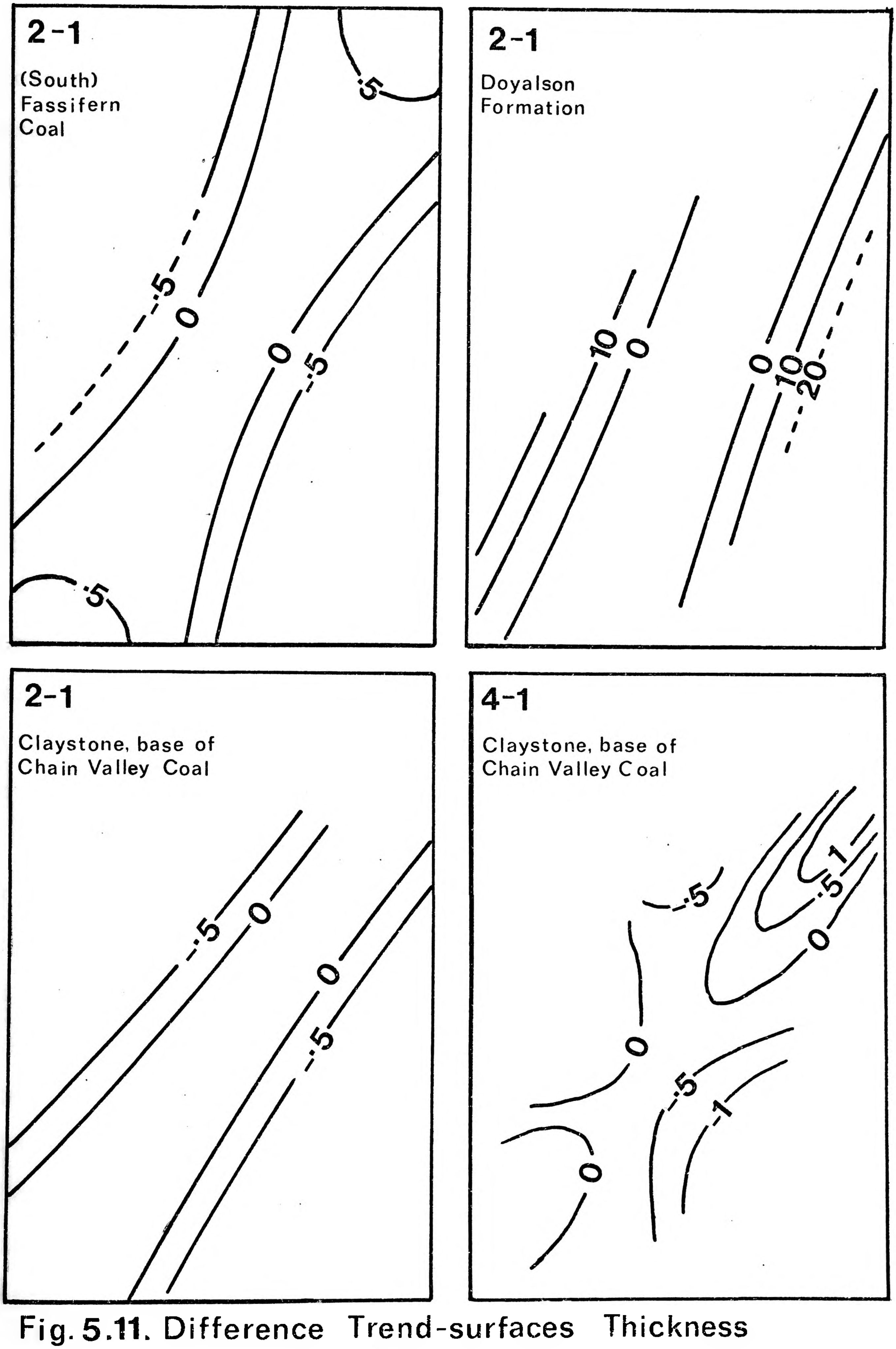


Fig. 5.11. Difference Trend-surfaces Thickness

coincides approximately with the Wyee Saddle. The thickness trends rise slightly from this point to the north and south along the main axis. However the variation component of the difference surface is only of the order of 0.5 m, again indicating that the second degree surface only offers a marginal improvement in the level of fit to the data.

b) Residuals (Fig. 5.12a,b)

As the trend-surfaces accounted for a very small percentage of the total variation the resulting residual maps have patterns similar to each other and similar to the thickness pattern of the raw data. The first and second degree residuals are presented to show the consistency of the extent and configuration of the residual domains when only a small proportion of the variation is accounted for by the trend. Only the first degree residuals are discussed.

Positive residual domains of the South Fassifern Coal and the South Fassifern Coal lie in two main areas. One is centred over the Chain Valley Bay area (upper right centre of Fig. 5.3a) and has values up to + 3m. This residual domain coincides with the Chain Valley Depression. Ridges in this positive domain extend to the northwest into an area of Fassifern Coal and east across the northern wedge of the Doyalson Formation into an area where the South Fassifern Coal is present. Tight closures in the southern part of the northern positive domain are probably due to inconsistent definition of the base of the seam where a local increase occurs

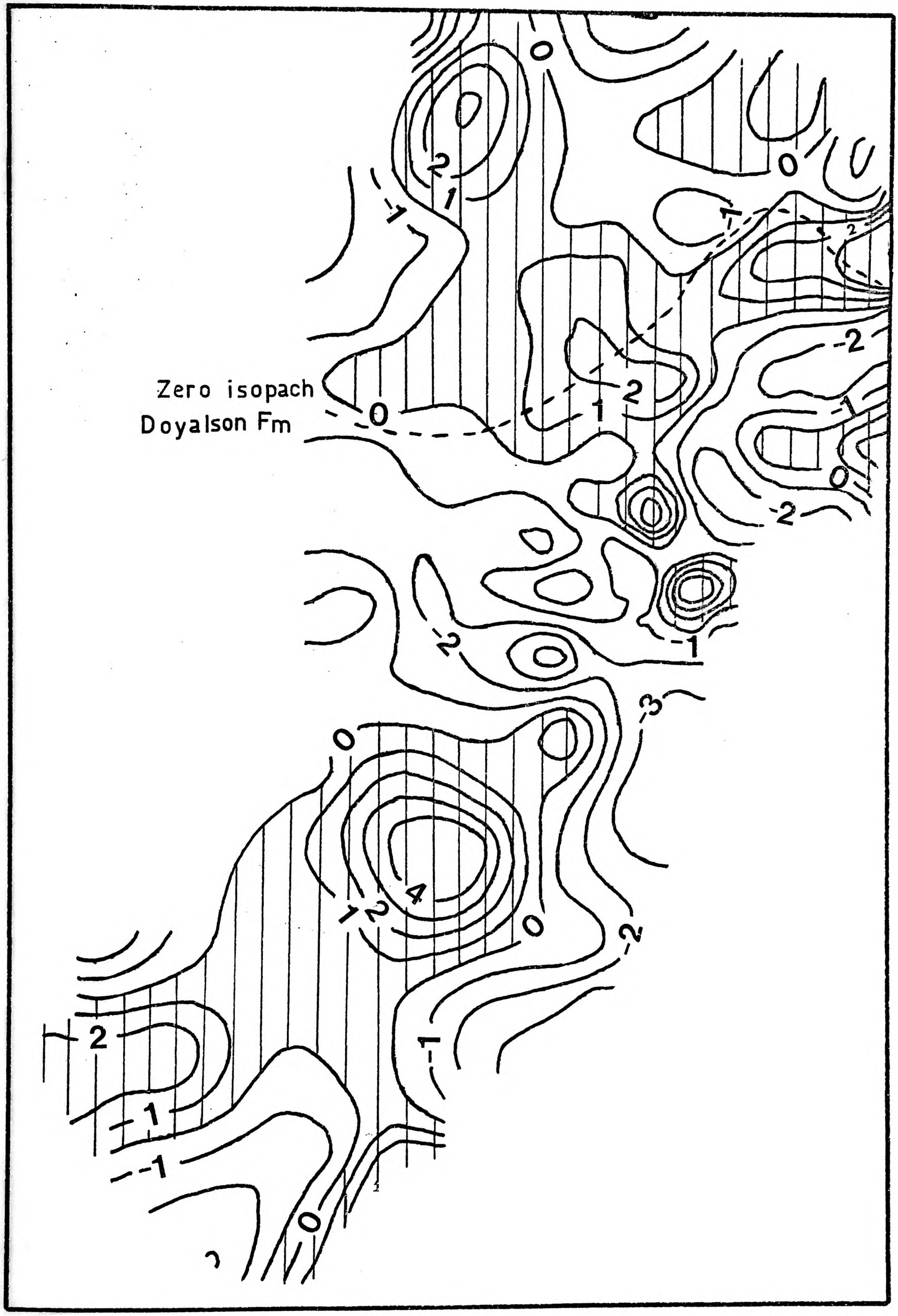


FIGURE 5.12a (South) Fassifern Coal - 1st Degree Thickness Residuals

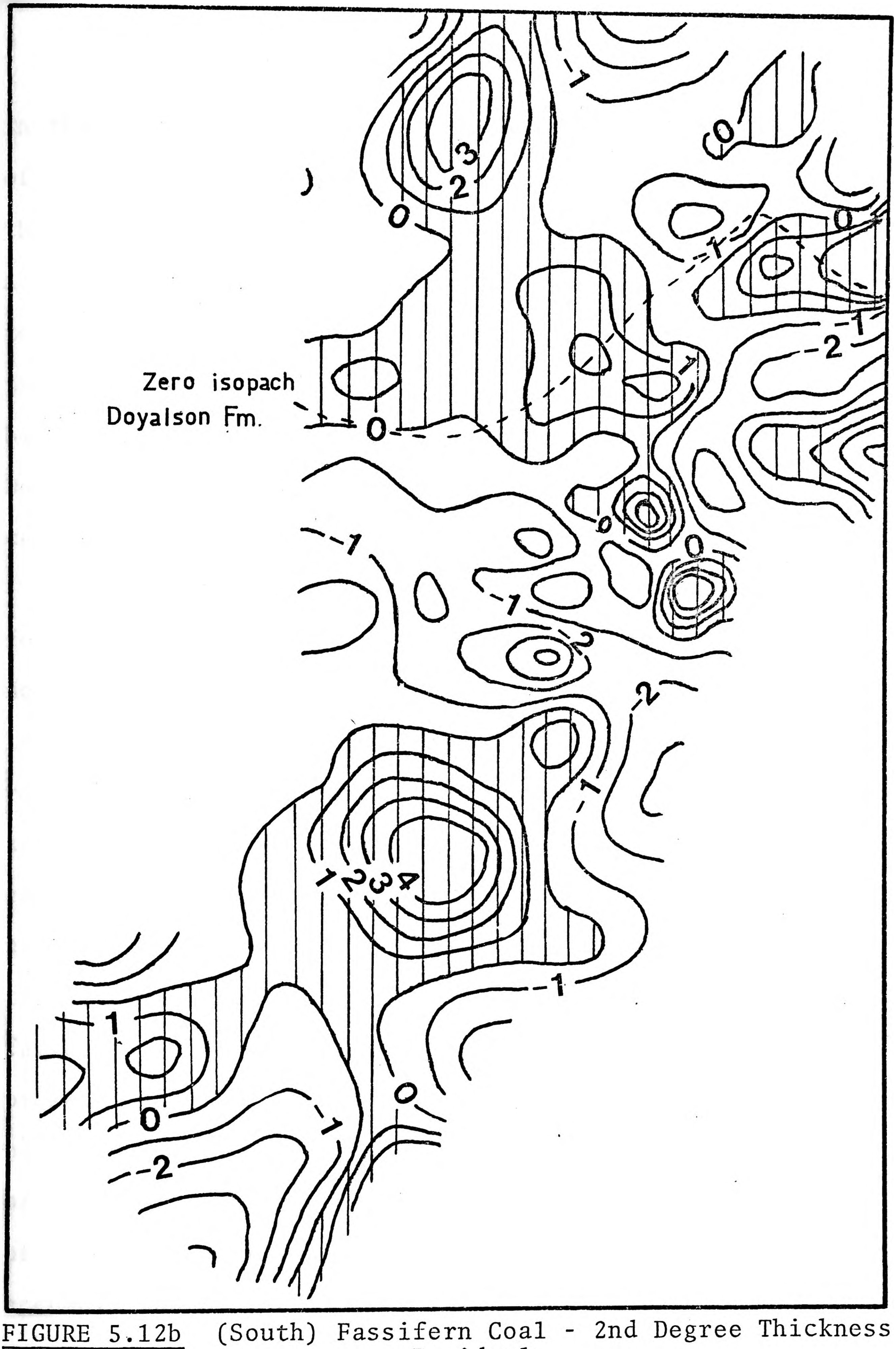


FIGURE 5.12b (South) Fassifern Coal - 2nd Degree Thickness Residuals

in the development of coal and carbonaceous shale at the base of the seam and hence increase the recorded thickness due to the lower compaction ratio for shale as compared with peat. Although part of the northwest ridge of the positive residual to the north may include the Chain Valley Coal equivalent in the Fassifern Coal, this factor does not appear to bias the residual domain with the line of zero isopach of the Doyalson Formation having little relationship to the configuration of the positive domain.

The second positive domain is a broad northeast trending feature with extrema up to + 4m. The large closure in the northern part of this domain is a persistent feature in the lower units of the M.I.B. and corresponds with an area of relatively poor development of the overlying Doyalson Formation and where the South Fassifern Coal consists largely of carbonaceous shale and minor coal plies. A borehole located at the centre of the positive maximum indicates an absence of the coarse facies of the Doyalson Formation: only the claystone facies (< 0.5m thick) which underlies the Chain Valley Coal is present. Similarly the Chain Valley Coal in this area is poorly developed as a few centimetres of coal in a sequence of light grey shales which grade into the overlying claystones of the Eleebana Formation. While conditions for the accumulation of coal in the southern positive thickness residual may have been relatively more favourable than adjacent areas the proportion of claystone bands within the South

Fassifern Coal in the southern part of the area studied is far greater than to the north. A possible contribution to the southern positive thickness residual is due to the increase in fine clastic units within the seam which, on compaction would result in a relatively thicker section than a corresponding coal (peat) unit. If the relatively lower compaction ratio of the South Fassifern Coal in the southern part of the Macquarie Syncline was taken into account in determining the planar regional thickness component the gradient of the regional increase in thickness would be intensified to the north.

Separating the two main positive thickness residuals is a narrow zone of negative thickness residuals which trends WNW across the Munmorah-Toukley area along the Wyee Saddle. In the centre part of the area of this negative residual the coal plies in the South Fassifern Coal are relatively well-developed with a thick section of coal (2-3m) which is currently worked in the Wyee State Coal Mine. Differential compaction of the coal relative to the southern shale-rich section of the South Fassifern may in part influence this area to report as a negative residual domain. However the thick coal section is relatively restricted in extent and the South Fassifern Coal throughout the domain is usually not well-developed. Negative residual thickness areas also flank the positive domains both to the east and west of the area studied.

5.4.2 Doyalson Formation: Thickness

a) Trend-Surfaces (Fig. 5.13)

All surfaces (Deg. 1-4) are statistically significant at an absolute level (Table 5.1), based on an F-test at a 95% confidence level. Only the added terms of the second degree surface represent a statistically significant improvement over the lower degree surfaces on the basis of an F-test of the additional variation explained by the quadratic terms; they explain 15% of the variation in the data. The first degree surface dips N 30 W and thickens to the south away from the region of the Fassifern Coal 'split'. The second degree surface (42% of variation) is a north-plunging synform pattern with a regional thickening along the axis (trending N 30 E) to the south and also thickening to the east and west away from the axis. The pattern of the regional thickness variation is further resolved in the degree 3 and 4 surfaces, and in the fourth degree surface the synform pattern becomes a restricted thin zone extending from the northwest across the line of the Macquarie Syncline. The narrow thickness synform feature is flanked to the east by a rapidly rising thickness trend. The zero isopach trend contour at the northern limit of the clastic wedge is sub-parallel to the structure trends for the Macquarie Syncline. The axes of the second degree trend-surfaces of the medium-coarse clastic phase of the Doyalson Formation and the (South) Fassifern Coal are approximately parallel but the thickening directions are reversed both along the axes and

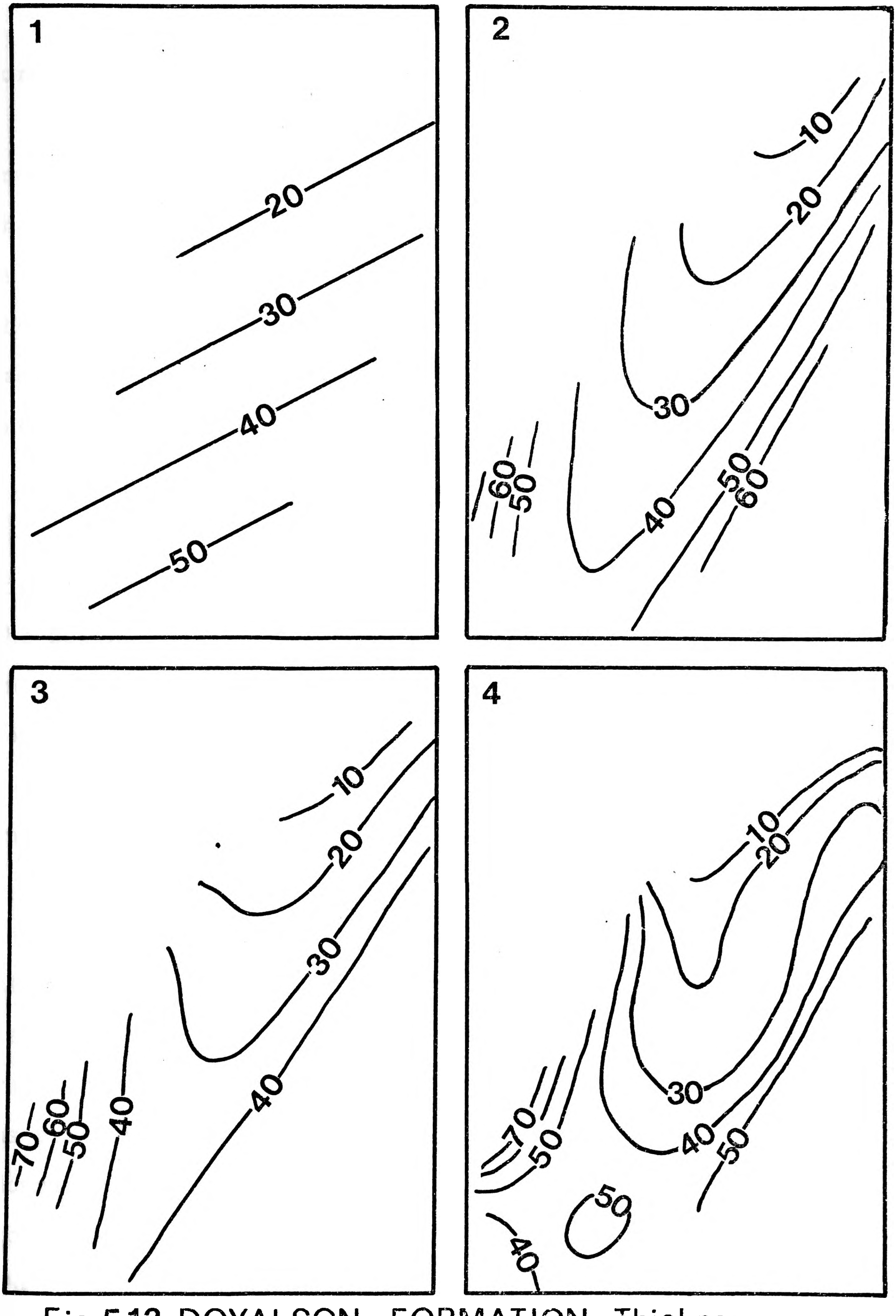


Fig.5.13. DOYALSON FORMATION – Thickness

Trend-surfaces Deg. 1-4

across the axes.

When the difference trend-surface between the second and first degree surface (Fig. 5.11) is inspected (i.e. with the pure second degree isolated) the synform pattern appears as a broad, open synform trough with relatively steep flanks. The axes of the difference surface (Deg. 2-1) for the (South) Fassifern Coal and the Doyalson Formation are almost parallel and coincidental.

b) Residuals (Fig. 5.14)

As only the second degree surface is a statistically significant improvement in fit the residual maps for all but the second degree residuals are omitted from this discussion. In any case the geographic configurations of the residual domains are virtually identical for all four residual maps due to the very high proportion of local serial autocorrelation in the thickness data.

Two main positive thickness domains occur. The first, in the north, corresponds to the thick tongue of coarse clastics which extends up to where the Fassifern Coal 'split' is initiated. The steep gradients in this region reflect the rapid development of the lower part of the Doyalson Formation as previously indicated in Fig. 2.8. A small negative residual domain almost enclosed by the northern positive residual corresponds to a localised area where the coarse clastics of the Doyalson Formation are very poorly developed (see Fig. 2.8), the section consisting largely of sandstone and claystone. The

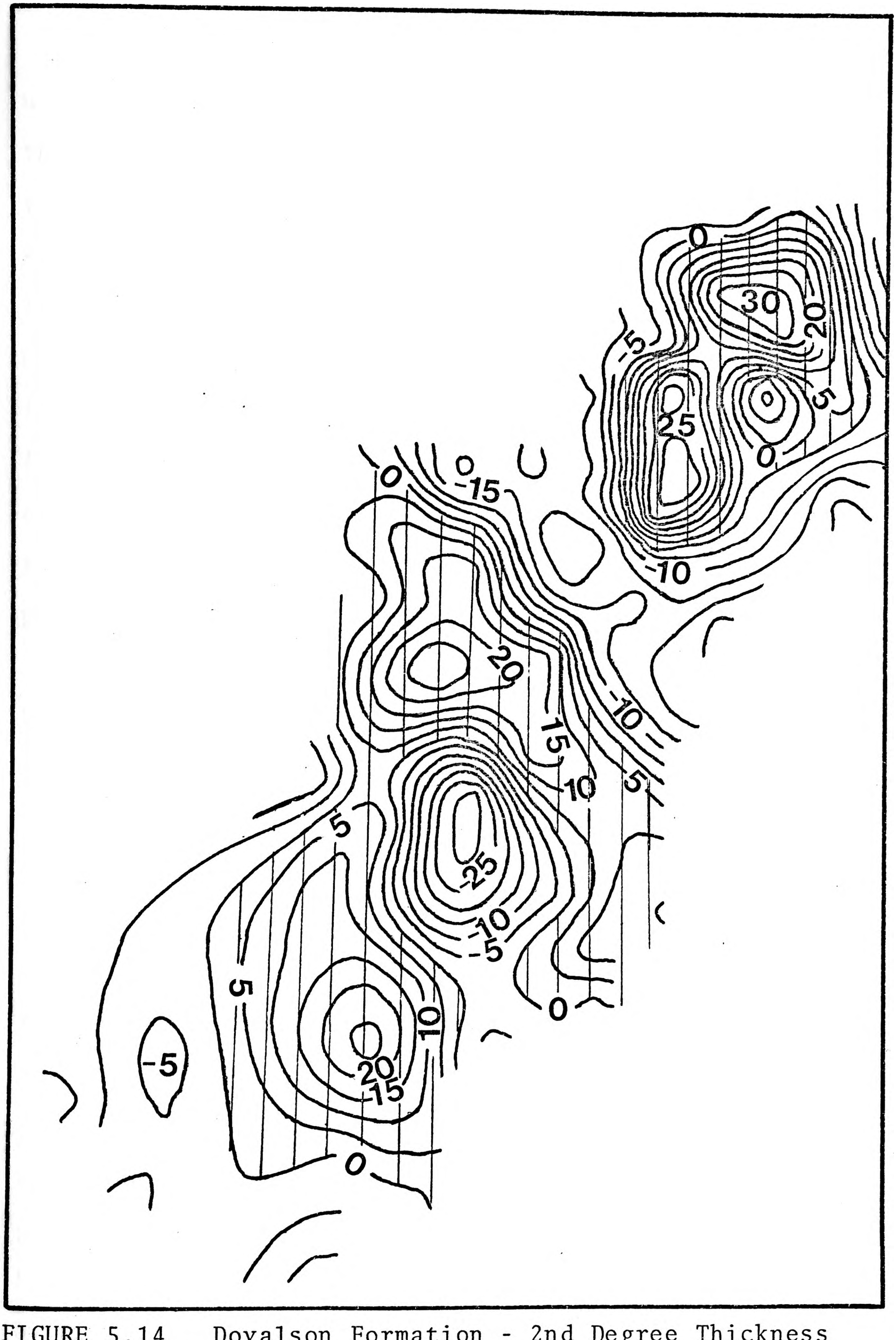


FIGURE 5.14 Doyalson Formation - 2nd Degree Thickness Residuals.

underlying South Fassifern Coal also has a local increase in the proportion of fine clastic bands. It would appear that the area of this small negative residual, during much of sedimentation period of the Doyalson Formation, was a bank feature flanked on both sides by channels in which the main bodies of conglomerate were deposited. For a low-meandering fluviatile environment of streams flowing in their own alluvium (in this case pebbles) the feature may perhaps be considered as a minor inter-channel island, persisting partly as a result of local differential compaction over a clastic-rich peat horizon of the South Fassifern Coal.

Around the thin margins of the clastic wedge of the Doyalson Formation is a steep negative residual area where the sandstone-conglomerate section passes laterally into a sandstone-claystone section as the zero isopach of the wedge is approached. To the south the negative residual area spreads into a broader northwest trending residual which occurs over the Wyee Saddle. Residual maps of the South Fassifern Coal thickness similarly indicated a negative thickness residual over the Wyee Saddle. South of the Wyee Saddle is another positive residual domain of greater extent than that to the north but having a close geometric resemblance to the northern positive domain. The southern domain is characterised by two high amplitude positive closures separated to the southeast by an isolated negative thickness residual, the centre of which is an area where only the claystone facies of the Doyalson

Formation is developed (< 0.5m thick). As noted in the previous section (5.3.1(b)) the South Fassifern Coal is poorly developed in the same area and consists largely of fine clastic bands and minor coal plies. Contemporary differential compaction of the South Fassifern Coal may have influenced channel patterns such that the area of negative residual remained starved of medium-coarse detritus and formed another inter-channel bank during the deposition of the Doyalson Formation.

The negative thickness residual over the Wyee Saddle may be considered as a major inter-channel feature receiving slightly more medium clastic detritus than the minor channel islands and controlled both by differential compaction and a lower rate of local tectonic subsidence.

5.4.3 Claystone, Base of Chain Valley Coal

This unit is the top unnamed member of the Doyalson Formation. The claystone, light brown in colour, is widely identifiable and underlies the Chain Valley Coal which may be present in varying degrees of development.

a) Trend-Surfaces (Fig. 5.15)

Although all surfaces are significant at a 95% confidence level using an absolute F-test only the fourth degree surface is a significant improvement over the first degree trend-surface. The fourth degree trend-surfaces (explaining 23% of the variation) has sufficient degrees of freedom to

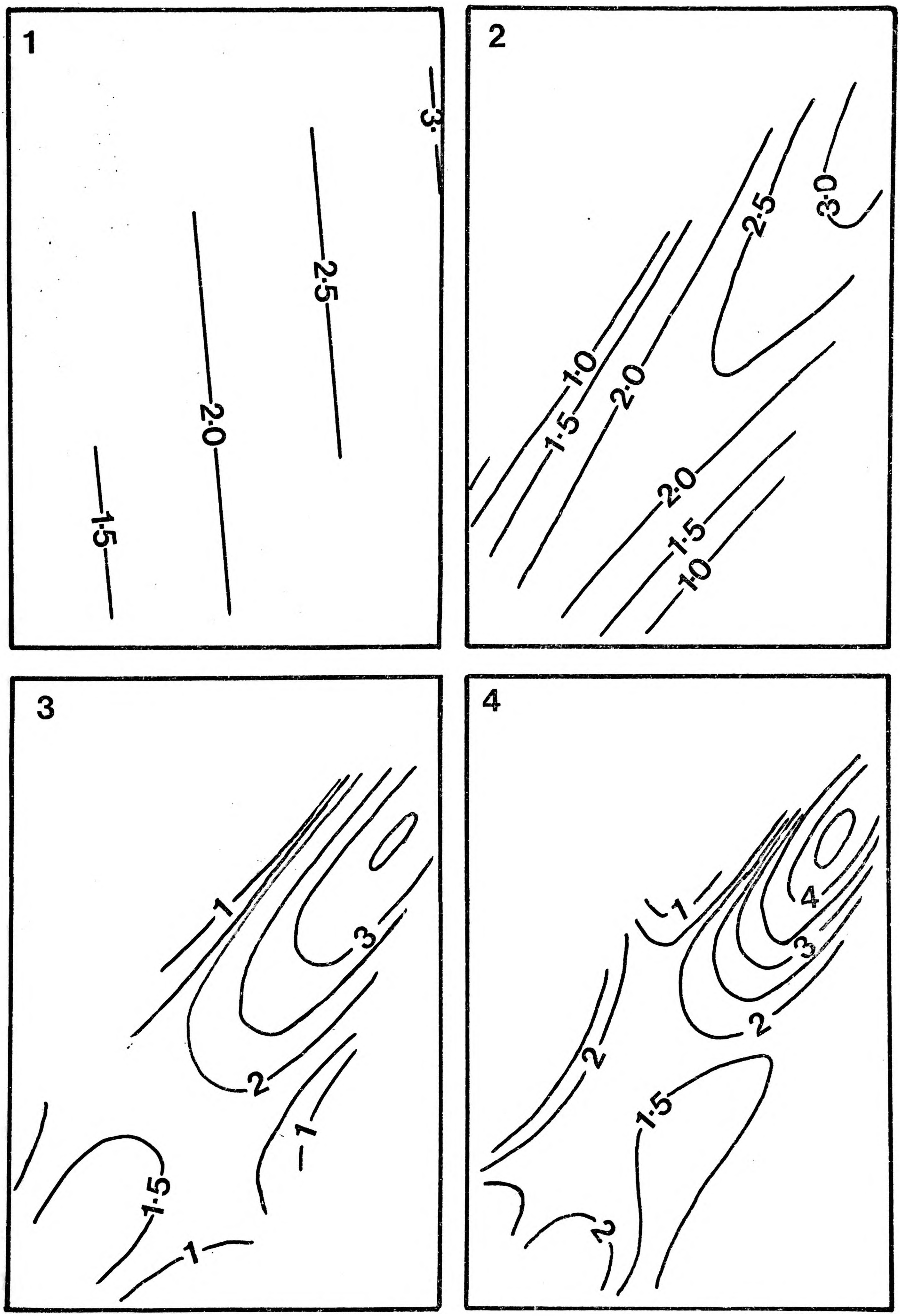


Fig.5.15.CLAYSTONE, FLOOR CHAIN VALLEY COAL - Thickness Trend-surfaces Deg. 1-4

accommodate localised features in the data and reveals a thickness maximum in the area close to the split of the Fassifern Coal. The thickness maximum is a result of the thick transitional phase of fine clastics at the base of the Chain Valley Coal. The claystone unit, although stratigraphically part of the Doyalson Formation, is treated separately as the approach of the study is to analyse lithosomes rather than stratigraphically-defined formations. There is a slight thinning of the fourth degree trend-surface to the south of the northern thickness maximum. This thinning is probably a reflection of both the thinning over the Wyee Saddle area and the reduction in thickness associated with the absence of the underlying coarse phase of the Doyalson Formation i.e. an inter-channel bank.

The second degree surface reveals a regional antiform thickness pattern plunging (thinning) to the south. Geometrically it is a reversal of the Doyalson Formation second degree thickness trend-surface both along its axis and normal to its axis. The sense of thickening is similar to that observed for the (South) Fassifern Coal.

The difference surfaces for Degree 2-Degree 1 and Degree 4-Degree 1 are given in Fig. 5.11. The Degree 2-Degree 1 isolates the weak second degree component which is a northeast trending antiform with a low broad positive domain along the Macquarie Syncline axis. The Degree 4-Degree 1 component which represents a statistically significant proportion of the variation (see Table 5.1) reveals the thickness maximum to the north flanked to the west and south by a broad thin area over the Morisset Anticline and the Wyee Saddle. A weak positive area lies to the far south and coincides with the negative structure residual domain referred to as the Wyong Slope.

b) Residuals (Fig. 5.16a,b)

The residuals from the second and fourth degree trend-surfaces are presented to show the persistence of the main autocorrelated residual domains with increasing degree of trend-surface; only the second degree residuals are discussed. The zone of thickening of the claystone in the 'hinge line' region of the Fassifern Coal 'split' has resolved as a high amplitude positive residual domain over the eastern and southern part of the area occupied by the Chain Valley Depression. To the south there is a large negative domain which corresponds partly with the zones of poorly developed Doyalson Formation. The negative residual domain is flanked to the east, west and far south by low amplitude positive domains. While the regional thickness variations of Doyalson Formation and its top claystone member tend to compliment one another, at a local scale, especially north from the area of the Wyee Saddle, there tends to be some degree of correspondence between positive and negative domains for the entire formation and its top member.

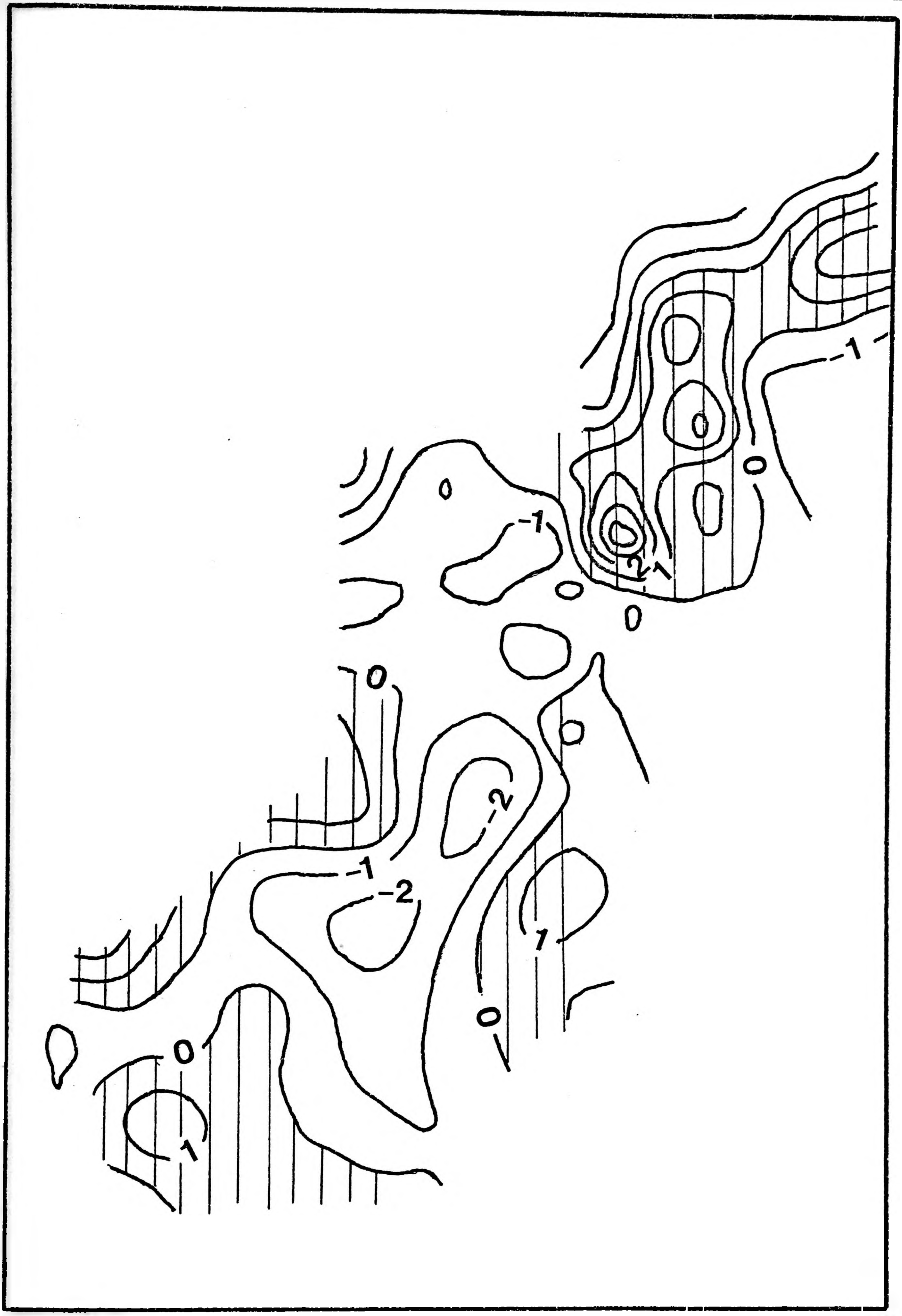


FIGURE 5.16a Claystone, Base Chain Valley Coal - 2nd Degree Thickness

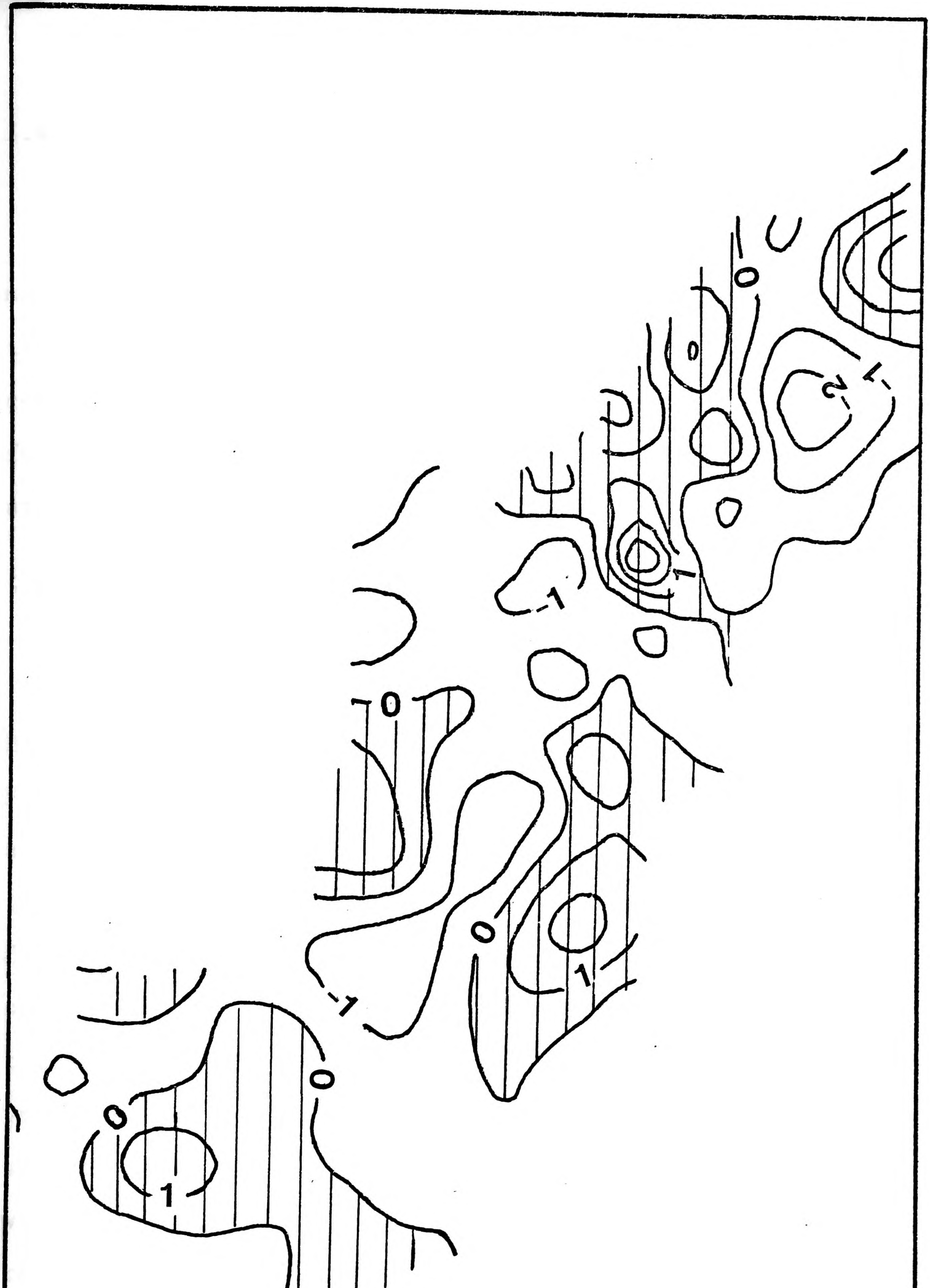


FIGURE 5.16b Claystone, Base Chain Valley Coal - 4th Degree Residuals

5.4.4 Chain Valley Coal: Thickness

a) Trend-Surfaces (Fig. 5.17)

The variation of the thickness of the Chain Valley Coal may be considered to have no statistically valid regional trend component (on the basis of an absolute F-test at 95% confidence level, see Table 5.1). The trend-surfaces account for only a few percent of the total variation. Residual maps are not presented.

5.4.5 Eleebana Formation: Thickness

a) Trend-Surfaces (Fig. 5.18)

Trend-surfaces (Deg. 1-4) for the thickness of the Eleebana Formation were all significant (based on an absolute F-test at a 95% confidence level). Only the third degree, accounting for 35% of the variation, resulted in a significant improvement (based on a F-test of the added terms) over the first and second degree trend-surfaces. The first degree surface is a plane, dipping in the direction of S 30 E i.e. thickening to the northwest. The second degree surface is very similar to the planar component. The third degree trend-surface reveals a parallel synform-antiform thickness pattern with axes trending N 45 E superimposed on a simple linear regional thickening to the northwest. The synform-antiform pattern plunges slightly to the southwest (i.e. slight thickening along the axes to the northeast). The thickening to the northwest is perhaps in part due to the presence of

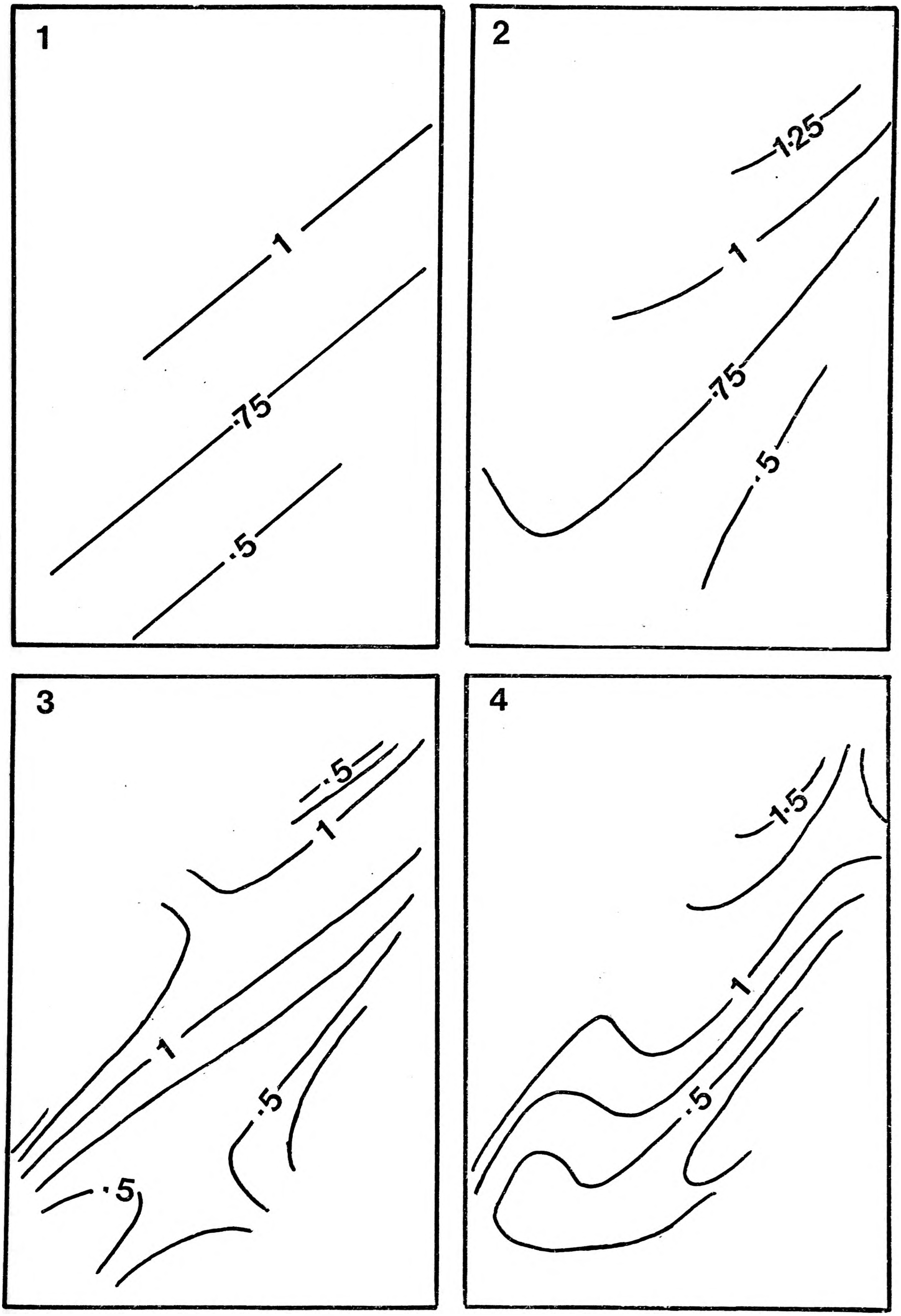


Fig.5.17. CHAIN VALLEY COAL – Thickness Trend-surfaces Deg. 1–4

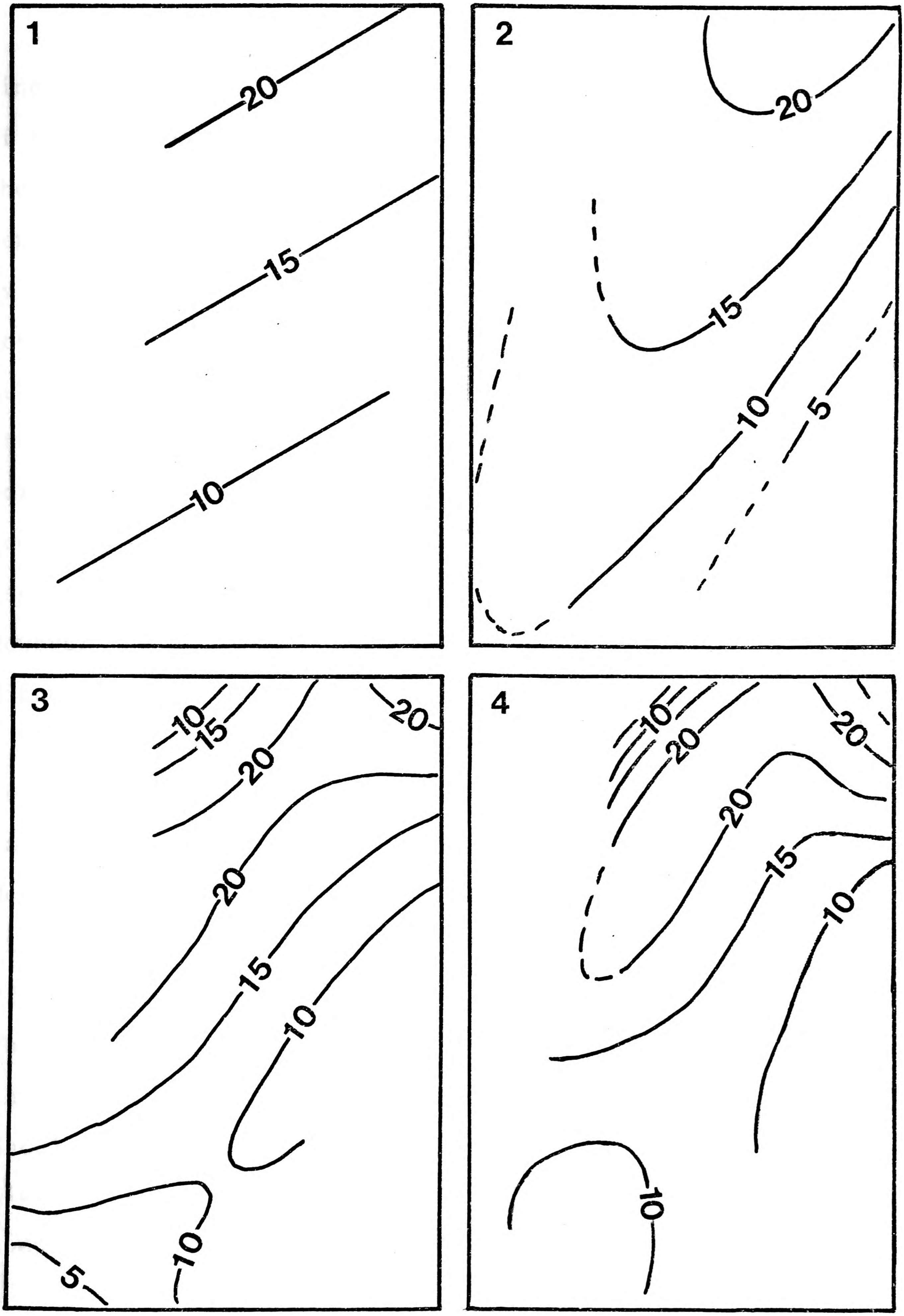


Fig.5.18.ELEEBANA FORMATION - Thickness

Trend - surfaces Deg. 1-4

fine conglomerate in the Eleebana Formation on the west side of Lake Macquarie as opposed to the remainder of the area where the Eleebana Formation consists of fine sandstone or claystone. Hence the apparent regional thickness variation may be caused by differential compaction of fine and coarse phases of the formation. It is also of interest to note that the thickness maxima in the higher degree trend-surfaces lie parallel and to the immediate northwest of the northern limit of the Doyalson Formation. Also there is no apparent relation in the geometries of the trend-surfaces to the structural domains isolated in the trend-surface analysis of the structure. However the implications of these observations will be discussed in Chapter 8.

Difference trend-surfaces are plotted in Fig. 5.19. The second degree component shows a very weak antiform pattern parallel to the Macquarie Syncline axis. The third degree difference surface (representing a statistically significant proportion of the variation) reflects the complexity of the variation of the thickness of the Eleebana Formation. The difference surface shows a positive feature extending along the Morisset Anticline and extending slightly into the Wyee Saddle area. The thickness patterns observed for the Eleebana Formation appear to be opposite and somewhat complimentary to those observed for underlying units.

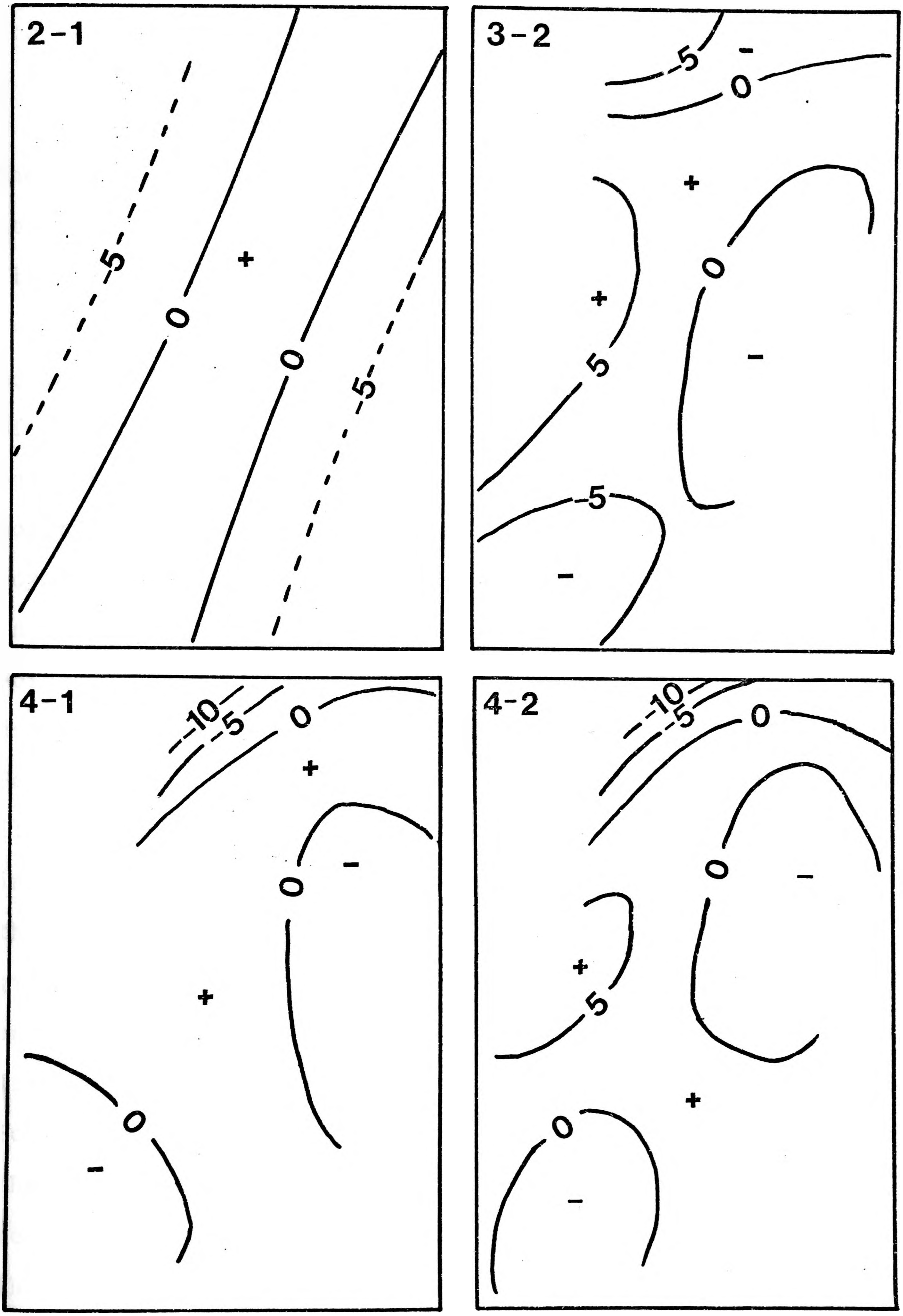


Fig. 5.19. Difference Trend-surfaces– Eleebana Fm. Thickness

b) Residuals (Fig. 5.20)

Residuals from the third degree trend-surface show that the high amplitude positive residual domains occur in the northwest outside the northern limit of the Doyalson Formation (i.e. where the Eleebana Formation directly overlies the Fassifern Coal). The zone of positive residuals also extends to the southwest across the large negative residual domain of the Doyalson Formation where the Doyalson Formation consists only of claystone and which separates the main northern positive residual from the southern positive areas in the Doyalson Formation. Likewise the small persistent closure in the southern part of the area present in the Doyalson Formation and suggested as a possible interchannel bank zone during the deposition of the coarse phase of the Doyalson Formation is revealed as a positive thickness residual in the Eleebana Formation. In this area there appears to be an inverse pattern between the signs of thickness residuals of the Eleebana Formation and the Doyalson Formation. The gradients of the residuals in the far south are relatively low and are partly a result of the lack of variation in the lithology of the Eleebana Formation. In the south the Eleebana Formation consists of claystones and fine sandstone while to the west side of Lake Macquarie coarse sandstone and conglomerate are locally present, causing rapid variations in thickness and steep residual gradients due, in part, to differential compaction of the coarse and fine facies.

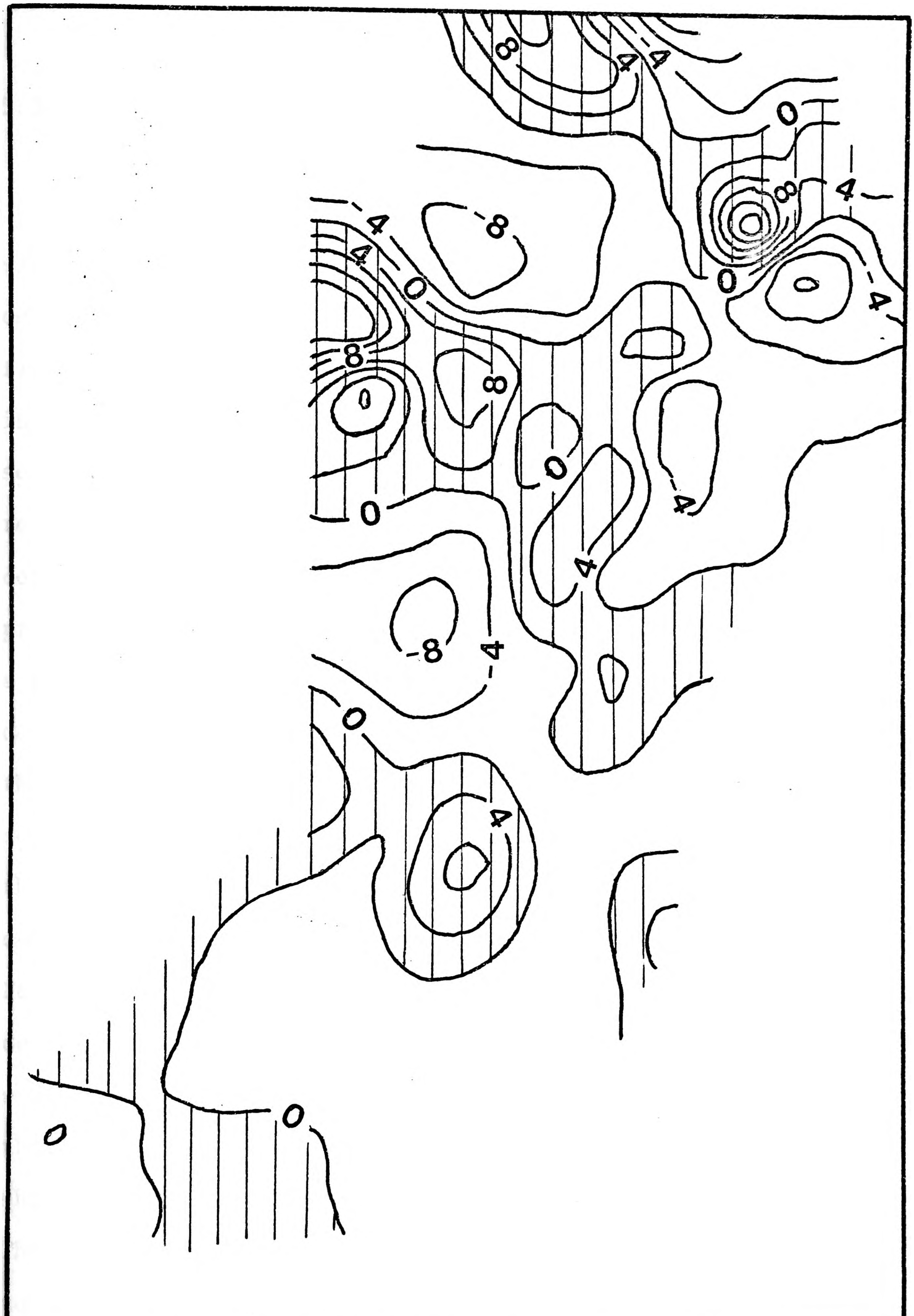


FIGURE 5.20 Eleebana Formation - 3rd Degree Thickness Residuals.

5.3.6 Great Northern Coal: Thickness

a) Trend-Surfaces (Fig. 5.21)

All surfaces are significant absolutely and represent significant improvements (on the basis of F-tests at a 95% confidence level) over lower degree trend-surfaces. The first degree surfaces (23% of the variation explained) dips in the direction N 30 W and thickens to the southeast. The second degree surface is somewhat featureless with a broad regional thickening to the south and southeast. The third degree trend-surface (49% of the variation explained) provides a more detailed resolution of the thickness and shows a parallel synform-antiform thickness trend of similar configuration to the third degree thickness trend-surface of the Eleebana Formation. The axes of the third degree surfaces for both these units strike in a northeast direction but the thickening sense in the Great Northern Coal is a reversal and compliments that of the thickness trend-surface of the Eleebana Formation. Thus the synform area in the Great Northern Coal coincides with an antiform area in the Eleebana Formation and *vice versa*. As noted the shape of the Eleebana Formation thickness trend was partly the result of lithological variations which, in turn, caused major thickness variations when compacted. The regional thickness pattern of the Great Northern Coal appears to a large extent influenced by the competence of the lithologies of the underlying Eleebana Formation. Hence

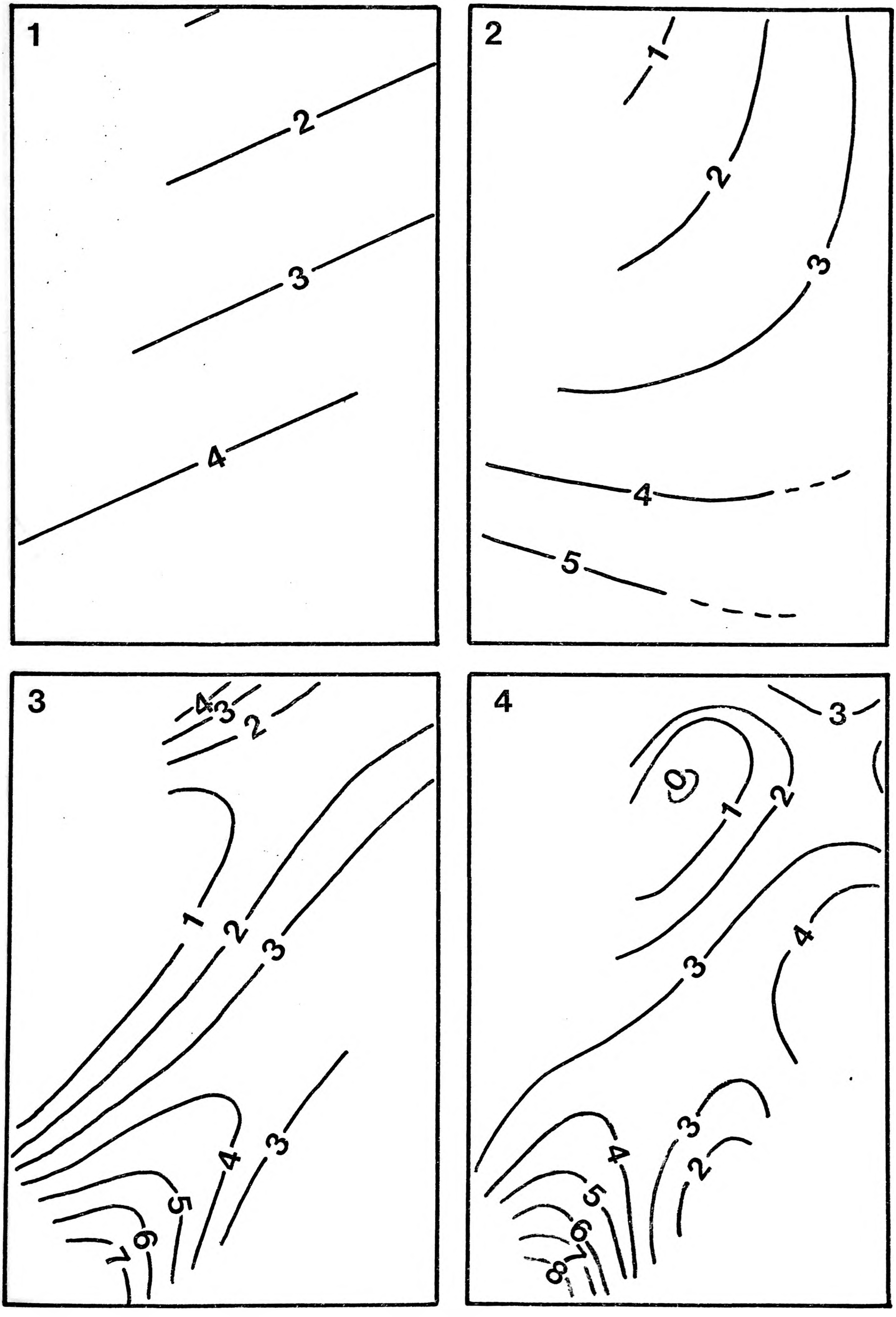


Fig.5.21.GREAT NORTHERN COAL - Thickness

Trend-surfaces Deg. 1-4

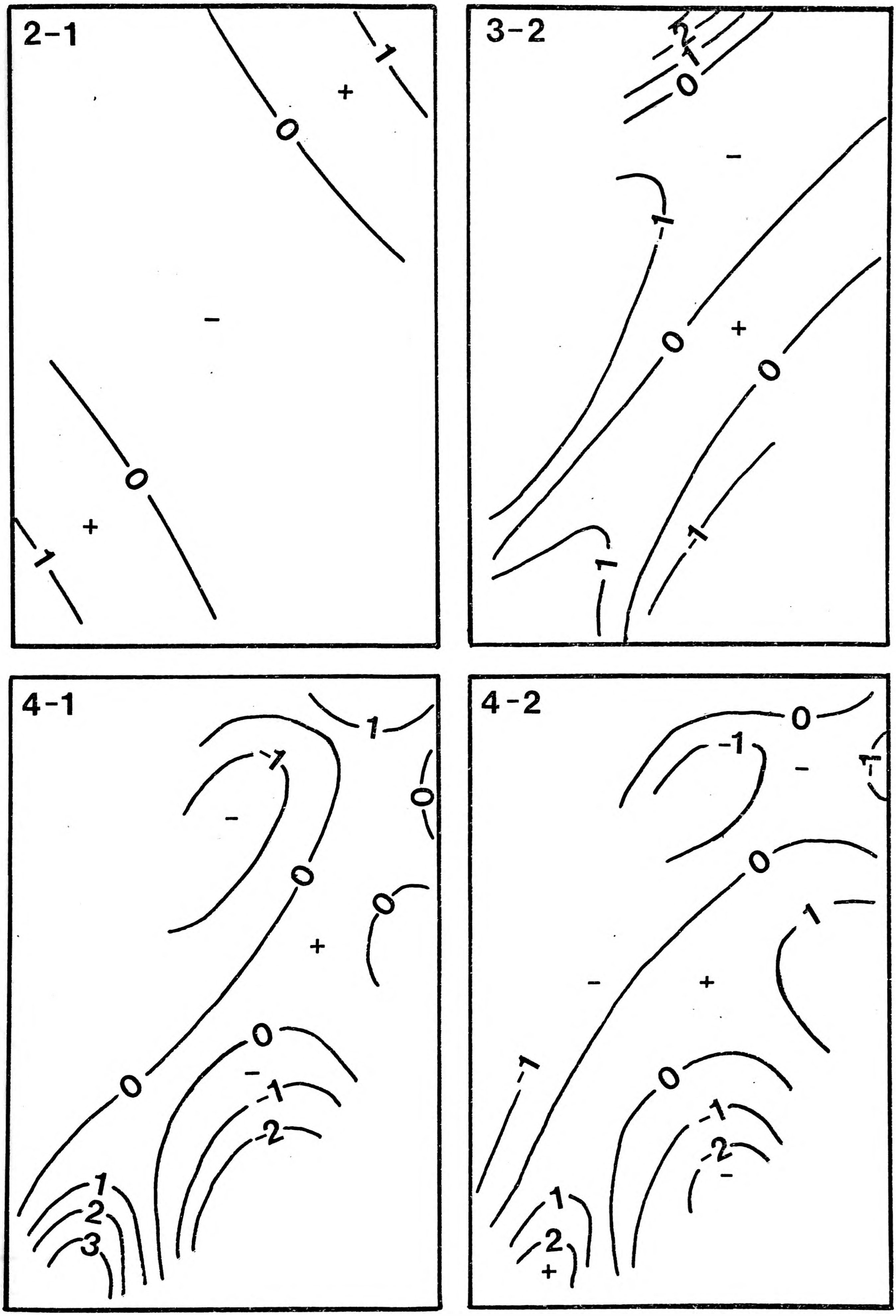


Fig. 5.22. Difference Trend-surfaces – Great Northern Coal Thickness

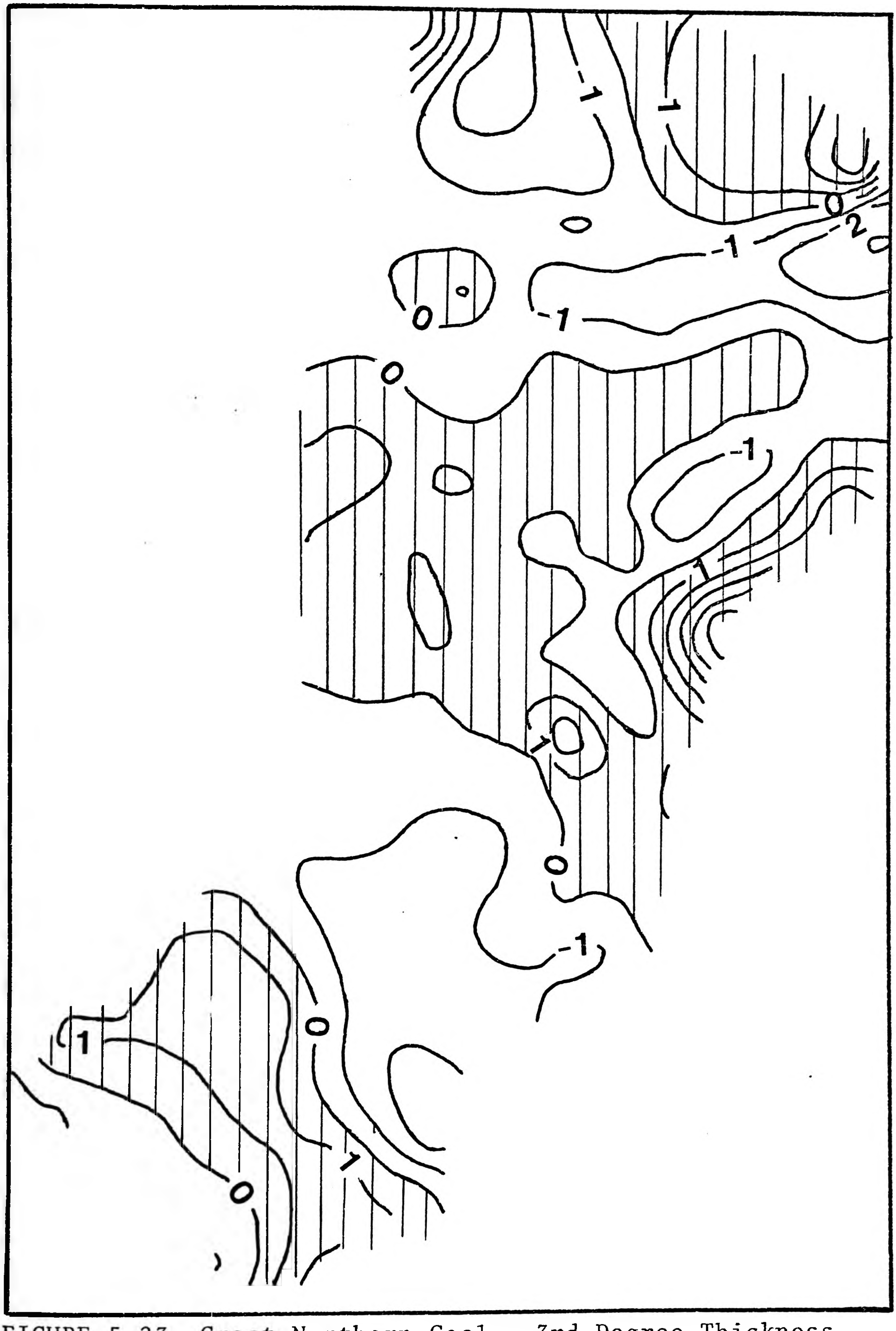


FIGURE 5.23 Great Northern Coal - 3rd Degree Thickness Residuals

relatively thin coal developed over the coarse facies of the Eleebana Formation as a result of slower compactional subsidence; the fourth degree surface (60% of the variation explained) provides a more complex resolution of the thickness variation.

The difference surfaces (Fig. 5.22) for the higher degree components isolate this synform-antiform trend more clearly. The second degree component would seem to be an over-simplification of the regional thickness variation.

b) Residuals (Fig. 5.23)

While each trend has significantly improved the fit to the data the actual configuration of the residual domains has changed very little with the different trend-surfaces; as before the main cause of the persistence of the residual patterns is the high level of local autocorrelation in the thickness data. As the third degree trend-surface appears to take into account the prominent trends in the data the residuals from the third degree trend are discussed. The third degree residuals were also selected because of an apparent inverse relation between the trends of the Eleebana Formation and the Great Northern Coal. Positive thickness domains occupy the central part of the area across the northern side of the Wyee Saddle, extending west onto the Morisset Anticline as well as in the south over the area of the Wyong Slope. A broad negative domain separates these two positive residuals and lies across, and parallels, the Wyee

Saddle. In the north a narrow negative zone extends across Lake Macquarie and is partly relatable to the coarse phase of the Eleebana Formation which is associated with a zone of positive thickness residuals. It is of interest to note that in this negative zone the Great Northern Coal, in a few bores, consists of a thin carbonaceous shale and coal sequence less than 1 m thick (e.g., Plate 2.4), or is not present. To the north of this negative residual is another positive residual which reflects a general increase in thickness of the Great Northern Coal beyond the northern limit of the area under study.

5.3.7 Claystone, Roof of Great Northern Coal: Thickness

This unit only occurs in isolated patches, the bulk of the claystone probably having been removed by erosion associated with the deposition of the Teralba Conglomerate Mb. Although the first degree trend-surface is a statistically significant fit at a 95% confidence level, it is considered to be of dubious geological value. Its geometry does not at this stage appear to be directly relatable to any of the features resolved by the analysis of the other units of the M.I.B. Channel relationships may become more apparent when roof-rock data from the collieries in the area are compiled and mapped. Results of the analysis of this unit are restricted to the statistics given in Table 5.1.

5.3.8 Teralba Conglomerate Member: Thickness

a) Trend-Surfaces (Fig. 5.24)

All surfaces are significant improvements in terms of an F-test at a 95% confidence level on the variation explained. The first degree surface accounts for 18% of the variation and is a plane wedge dipping in the direction S 50 W and thickening to the north. A southern thinning trend is present on all trend-surface maps and is related to the absence of conglomerate in the far south of the area. The section thins rapidly down to 5 m of sandstone in the Wyong area and southwest of Wyong consists of 2-3 m of sandstone. The second degree surface, accounting for 40% of the variation, is a broad, flat-topped paraboloid dipping only on its southern flank to accommodate the thin sandstone-rich Teralba Conglomerate Mb. that occurs in the Wyong area. The facies change in the Teralba Conglomerate Mb. begins across, and parallel to, the Wyee Saddle where the proportion of conglomerate decreases and sandstone predominates. The conglomerate is absent from the formation a few kilometres south of the Wyee Saddle.

The third degree surface, accounting for 48% of the variation, provides a more detailed resolution of the regional variation. It shows a thick spur of sediment with a north-south axis trending from the northwest side of the area down towards the centre of the area along the Morisset Anticline. This thick tongue of sediment thins regionally to the east and

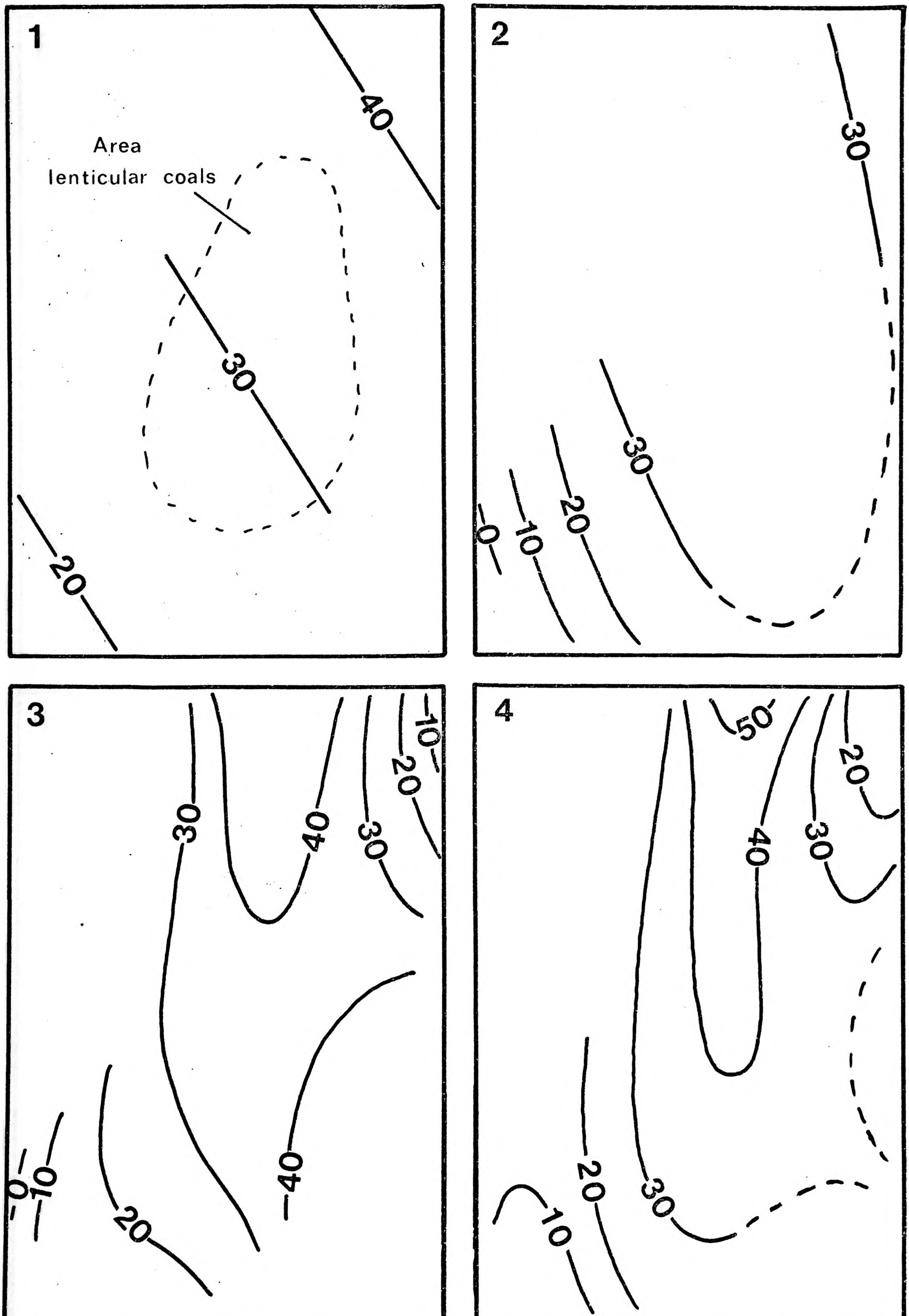


Fig.5.24.TERALBA CONGLOMERATE MEMBER –

Thickness Trend-surfaces Deg. 1-4

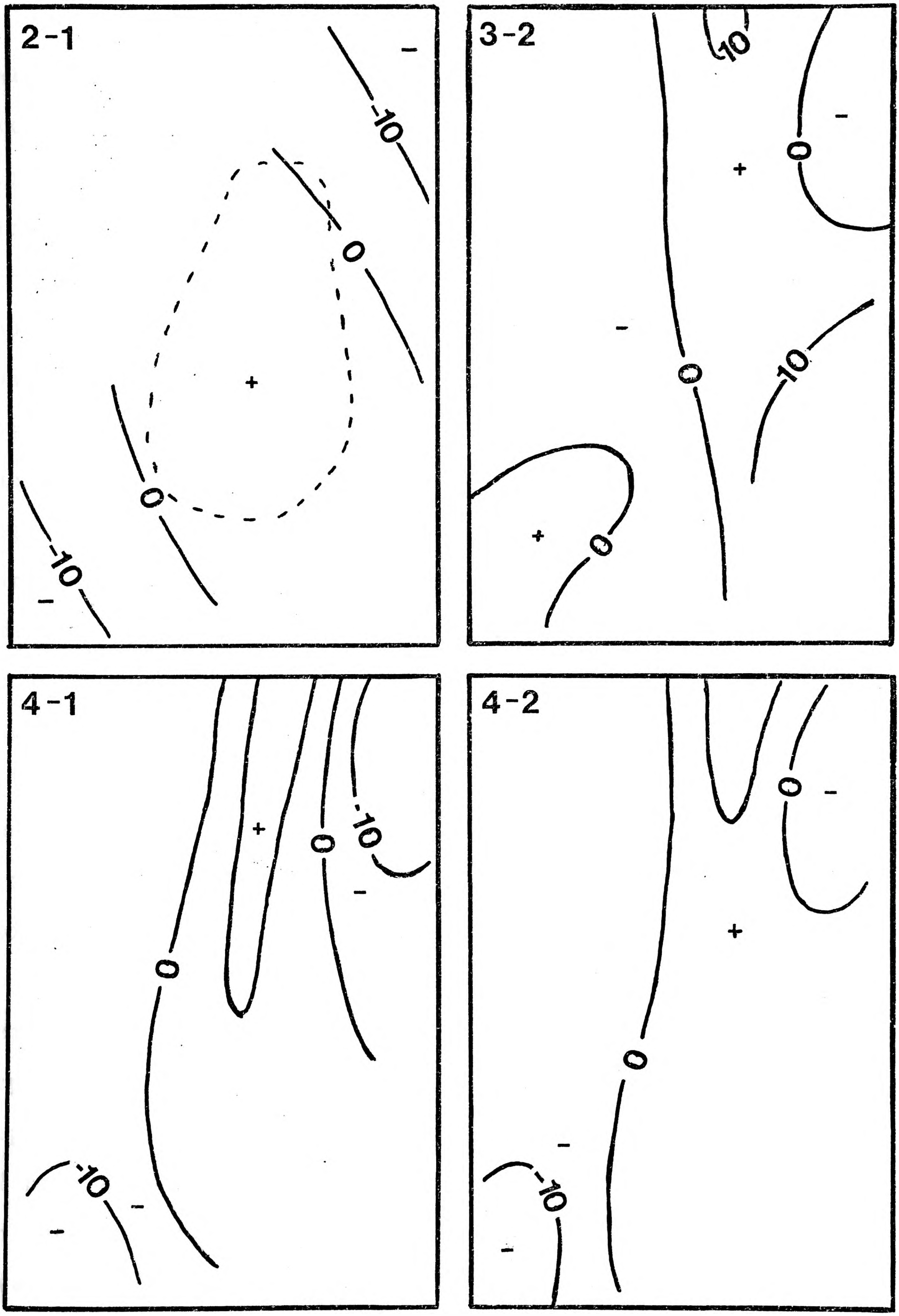


Fig. 5.25. Difference Trend-surfaces – Teralba Conglom. Mb. Thickness

southwest but extends slightly along the Wyee Saddle. This maximum thickness trend corresponds approximately with the regional thickness minimum in the Great Northern Coal and the thickness maximum in the Eleebana Formation. Although the rapid thinning of the Teralba Conglomerate Mb. to the far south coincides with a thickness maximum in the Great Northern Coal the thinning is more likely to be assocated with a possible barring effect of a more slowly subsiding zone along the region of the Wyee Saddle. Also a major cause of the regionally thin Teralba Conglomerate Mb. in the east and northeast of the area is the far greater compaction ratio of the Toukley and Buff Point Coal Lenses which generally do not occur to the west of the area. The difference in compaction may in fact have effectively obliterated any obvious structure-thickness relationship which influenced sedimentation during the deposition of the Teralba Conglomerate Mb. Although fine clastic units probably equivalent to the Toukley and Buff Point Coal Lenses occur along the west of the area it is not possible to correlate reliably them and consequently the Teralba Conglomerate Mb. cannot be subdivided into three separate lithosomes consistent with the interruption of the deposition of the conglomerate by areally restricted periods of peat accumulation. The effect of these minor coal units on the deposition of the Teralba Conglomerate Member is evaluated further in Chapters 7 and 8.

Difference maps for the trend-surface are given in Fig.

5.25. The second degree component, isolated in the Degree 2-Degree 1 surface, shows the weak positive area in the northwest trending through the area; the higher degree components resolve this trend as the elongate positive feature present in the third and fourth degree trend-surfaces in Fig. 5.24. The elongate positive zone which lies along the axis of the Morisset Anticline, is flanked to the east by a negative area over the Chain Valley Depression. As pointed out above the presence of the Toukley and Buff Point Coal Lenses within the section of the Teralba Conglomerate Mb. and the large difference of the compaction ratios may well be the cause of the observed relationship between the thickness trends and present-day structural domains, rather than indicating any direct causative mechanism.

(b) Residuals (Fig. 5.26)

The residuals from the trend-surfaces are dominated by a large amplitude positive in the northwest of the area. The large positive residual domain extends east from the Morisset Anticline into the area of the Chain Valley Depression and partly corresponds with an area of very thin Great Northern Coal (perhaps caused by erosion). The trend-surfaces have probably been somewhat biased by the presence of this high amplitude positive feature but most of the data variation still reports to the residuals. On the third degree residuals map the tight positive domain is surrounded by a low amplitude

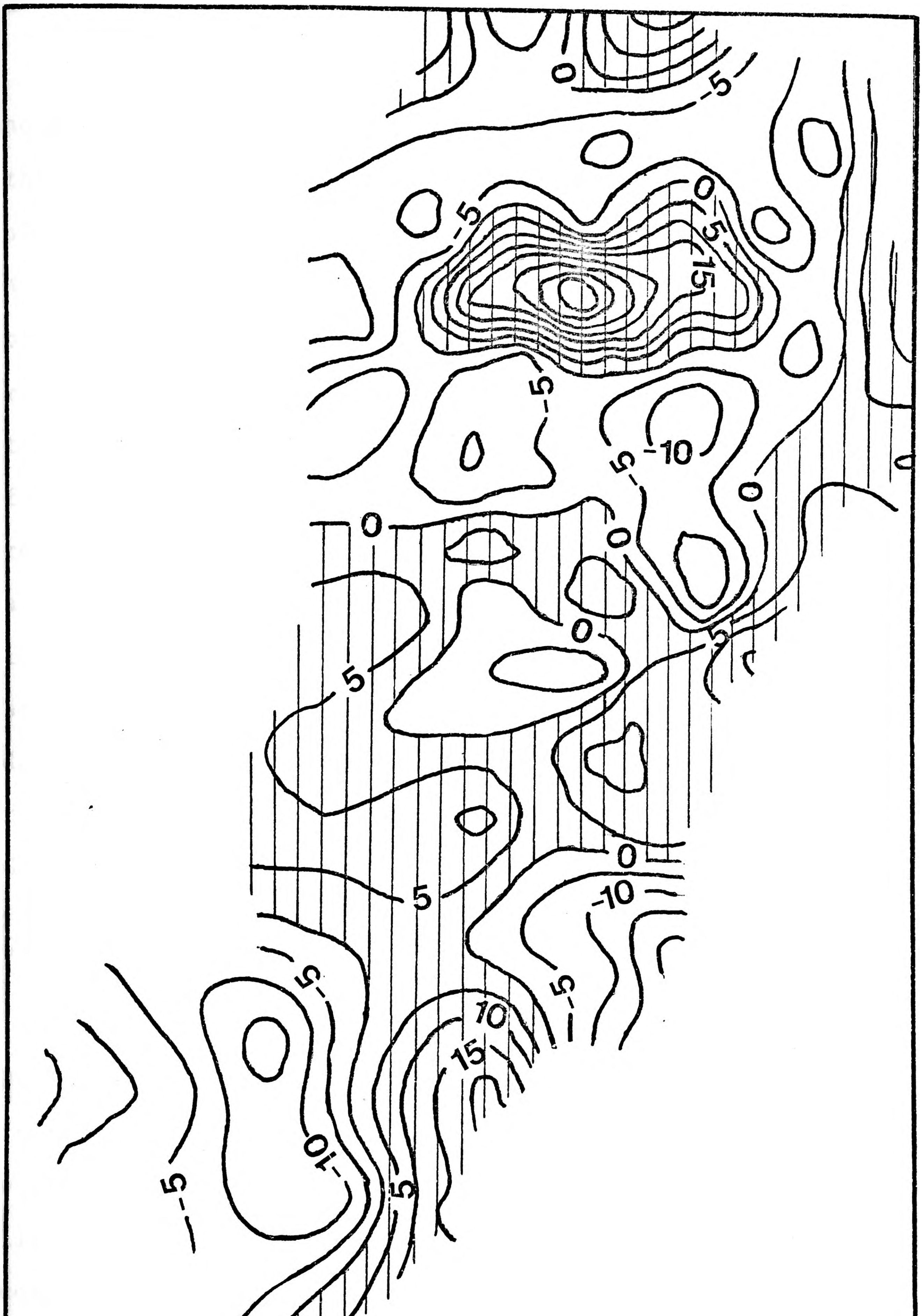


FIGURE 5.26 Teralba Conglomerate Mb - 3rd Degree Thickness Residuals

negative residual domain partly in response to the rapid local thickening in the Teralba Conglomerate Mb. To the far east along the Swansea Rise and extending south to the area of the Wyee Saddle is another large zone of positive residuals. South of, and roughly parallel to the Wyee Saddle is a negative residual domain whose gradients reflect the rapid decrease in thickness of the Teralba Conglomerate Mb. with the sudden facies change. The pinch-out zone is quite obvious with residuals changing from +5m to -10m over a distance of approximately 3 kms. Except for the strong positive domain in the north perhaps having some causative relation to the area where the Great Northern Coal is poorly developed, there does not appear to be any strong relationship between the residuals of the Teralba Conglomerate Mb. and the underlying Great Northern Coal thickness residuals.

5.4.9 Buff Point Coal Lens and the Toukley Coal Lens: Thickness

While the thickness variations of the two coal units, the Buff Point Coal Lens and the Toukley Coal Lens are of interest in terms of local features of the Teralba Conglomerate Mb., within which these units are wholly confined, they are of limited regional value. The trend-surfaces are presented for completeness in Figs. 5.27 and 5.28. A planar trend was significant (based on an F-test at a 95% confidence level on the variation explained by the linear terms for the Toukley Coal Lens. The positive residuals from the first degree

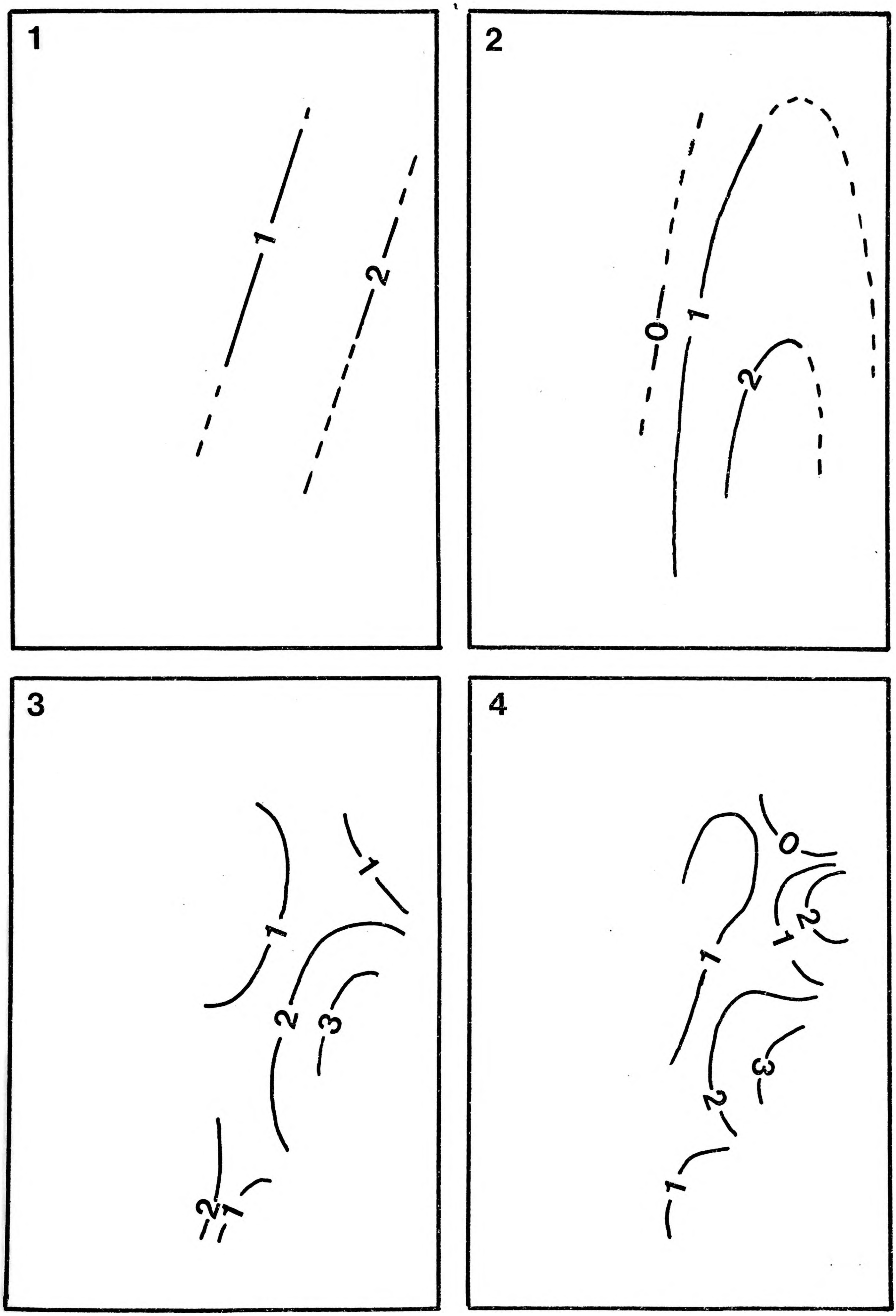


Fig.5.27. BUFF POINT COAL LENS – Thickness

Trend-surfaces Deg. 1-4

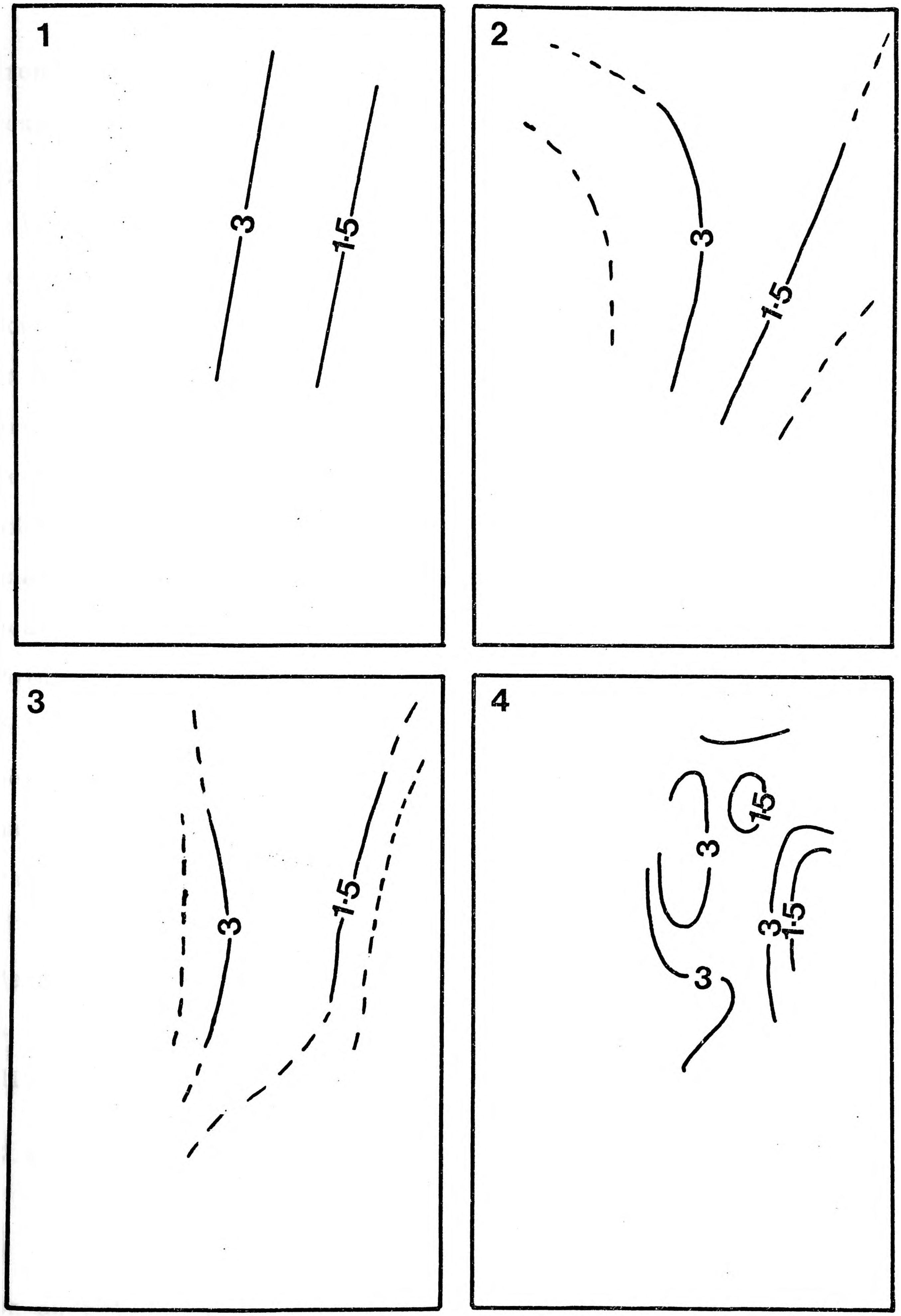


Fig.5.28.TOUKLEY COAL LENS - Thickness Trend-surfaces Deg. 1-4

trend-surface for the Toukley Coal Lens (Fig. 5.29) show a weak positive domain extending north-south along the west side of the Chain Valley Bay Depression. Negative residuals extending onto the Morisset Anticline occur partly in response to the high value of the trend-surface in the west of the area. However it is felt that this trend may result from an increase in the thickness of the unit caused by an increase in the proportion of claystone in the section rather than thicker coal section. In light of the inconsistency in the lithologies of these lenticular coal units the results of the trend analysis are of doubtful reliability. The regional extent of peat accumulation (and preservation) associated with the Buff Point Coal Lens and the Toukley Coal Lens are perhaps of more relevance in terms of contemporary structural control on the peat accumulation than actual thicknesses of the minor coal units which vary rapidly in their lithologies (and compaction ratios).

The Toukley Coal Lens has a slightly wider area of development than the Buff Point Coal Lens but both tend to have a slightly elongate development with an axis running in a NNE direction along the axis of the Macquarie Syncline.

5.4.10 Mannering Park Claystone Member: Thickness

(a) Trend-Surfaces (Fig. 5.30)

All trend-surfaces were statistically significant (based on an F-test of all terms at a 95% confidence level) although

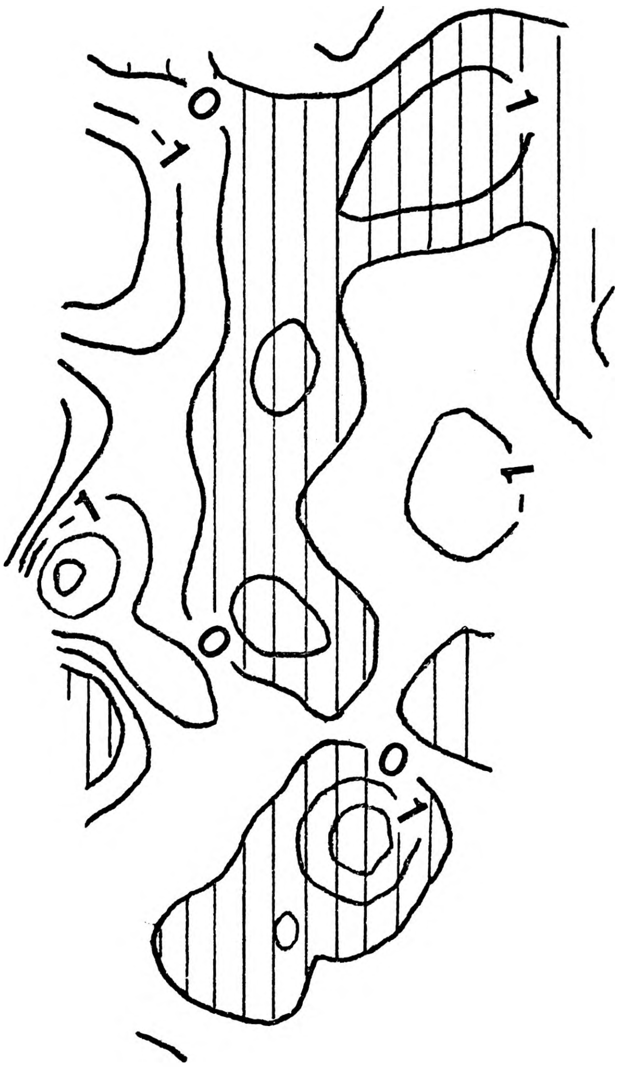


FIGURE 5.29 Toukley Coal Lens - 1st Degree Thickness Residuals

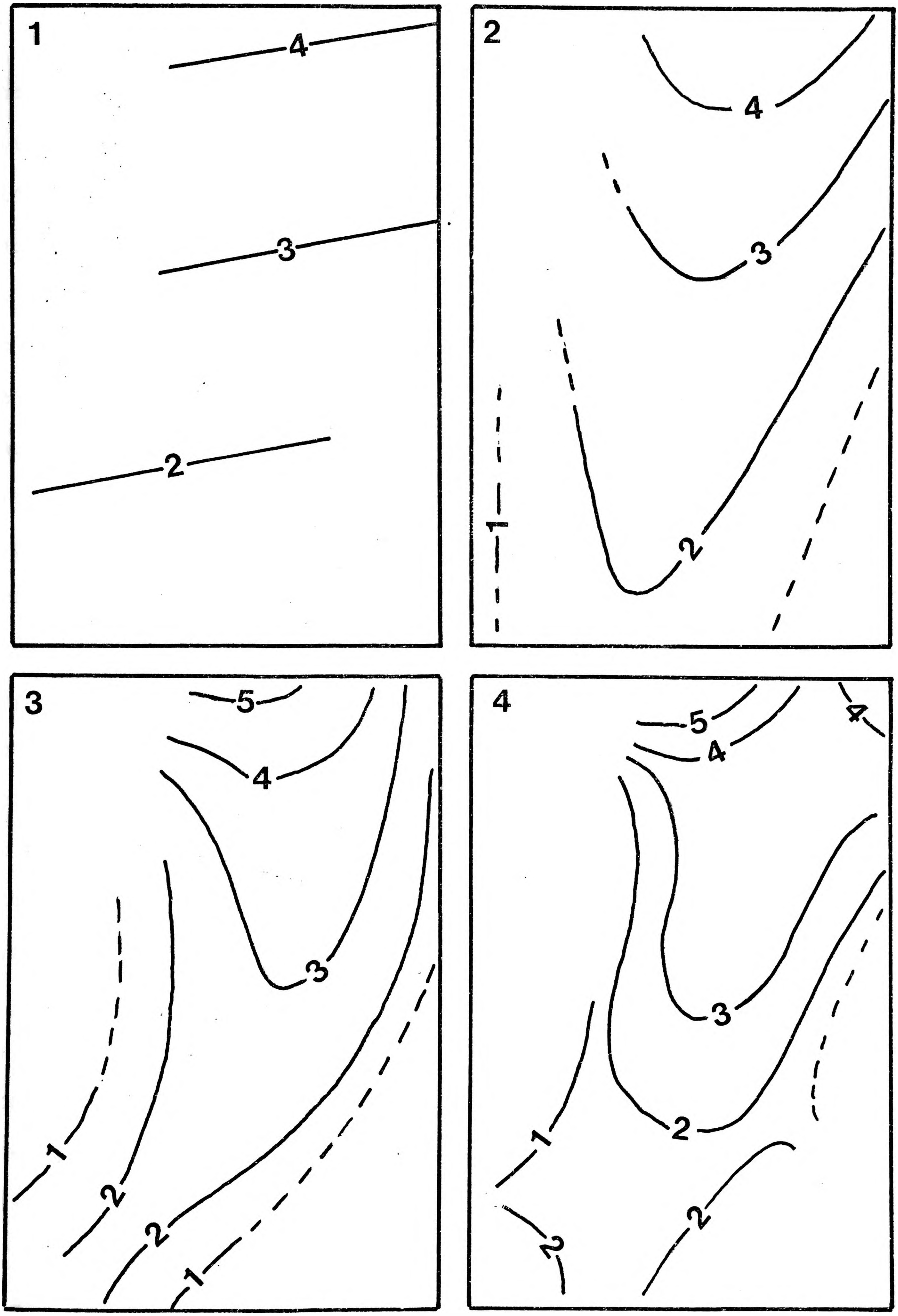


Fig.5.30.MANNERING PARK CLAYSTONE MEMBER - Thickness Trend-surfaces Deg. 1-4

the higher degree surfaces did not significantly improve the fit over the first degree surface. The first degree surface (14% of the variation explained) dips to the south (S 10 E) and shows a regional planar thickness trend increasing to the north. The second degree surface is a south plunging antiform surface regionally thinning to the south and to the east and west of the area. The third and fourth degree trends resolve the regional thickness pattern into a narrow ridge with its axis running from the far north of the area into and along the Macquarie Syncline axis and extending south to the Wyong Slope area. However while these higher degree trend-surfaces do not represent statistically significant improvements over the lower degree surface, their geometry does appear to have some geological relevance. The trend patterns are consistent with features observed in trends of some of the underlying formations, i.e., the antiform-synform thickness trends with northeasterly axes parallel and coincidental with the Macquarie Syncline axis.

Difference trend-surfaces are given in Fig. 5.31. The prominent positive trend which is isolated in the high degree components of the difference trends runs north-south through the area. It is flanked by narrow negative zones to the east west and southeast. The difference trends support the results of the trend-surfaces of the thickness of the Mannering Park Claystone Member and suggest a regional thickening in towards the axial region of the Macquarie Syncline.

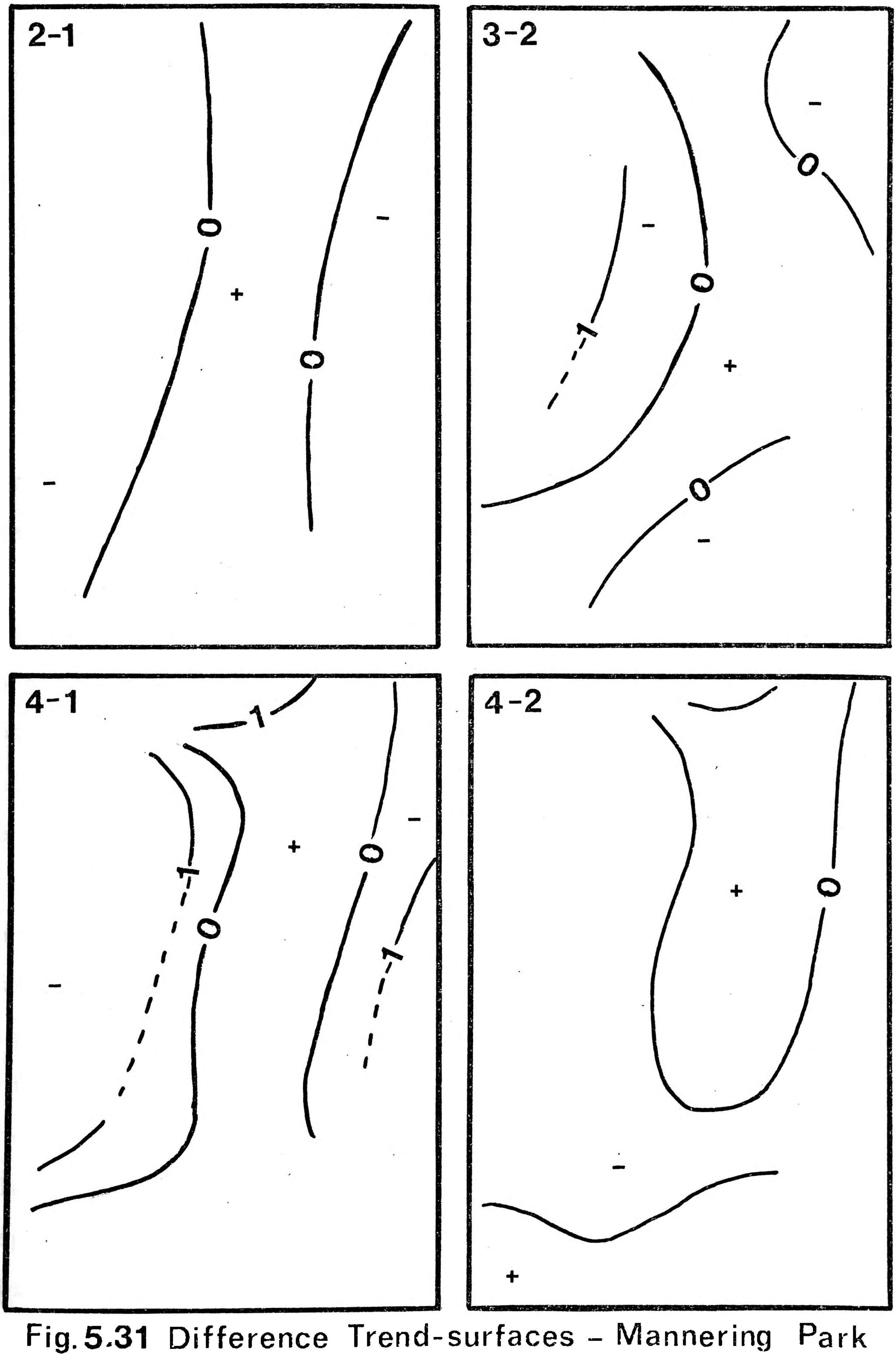


Fig. 5.31 Difference Trend-surfaces - Mannering Park Claystone Mb. Thickness

(b) Residuals (Fig. 5.32)

As the trends do not significantly improve the fit at each degree the spatial distribution of the residual domains changes very little with each degree trend-surface. The second degree residuals are discussed as the second trend-surface is considered a sufficient and adequate representation of the regional thickness variation of the Mannering Park Claystone Mb. The residual domains are highly localised and in the north are characterised by adjacent, elongate, north-south trending zones of positive and negative residuals. The zone of positive residuals occupies part of the area of the Morisset Anticline, running along that structure and linked in the south to another positive area along part of the Swansea Rise. The positive residual almost encloses a negative residual domain which is centred over the inner part of the Chain Valley Depression. Negative residuals also occur to the far west along the Morisset Anticline and extend to the south across part of the Wyee Saddle. Positive domains also occur on the Wyee Saddle and to the far south over the Wyong Slope. The large negative domain to the extreme north more or less skirts the intermediate zone between the extrema of the Morisset Anticline, the Chain Valley Depression and the Swansea Rise. The claystone does not continue to thicken into the Chain Valley Depression where the overlying Wallarah Coal is locally thickest, but thins. Although there is some relation in the

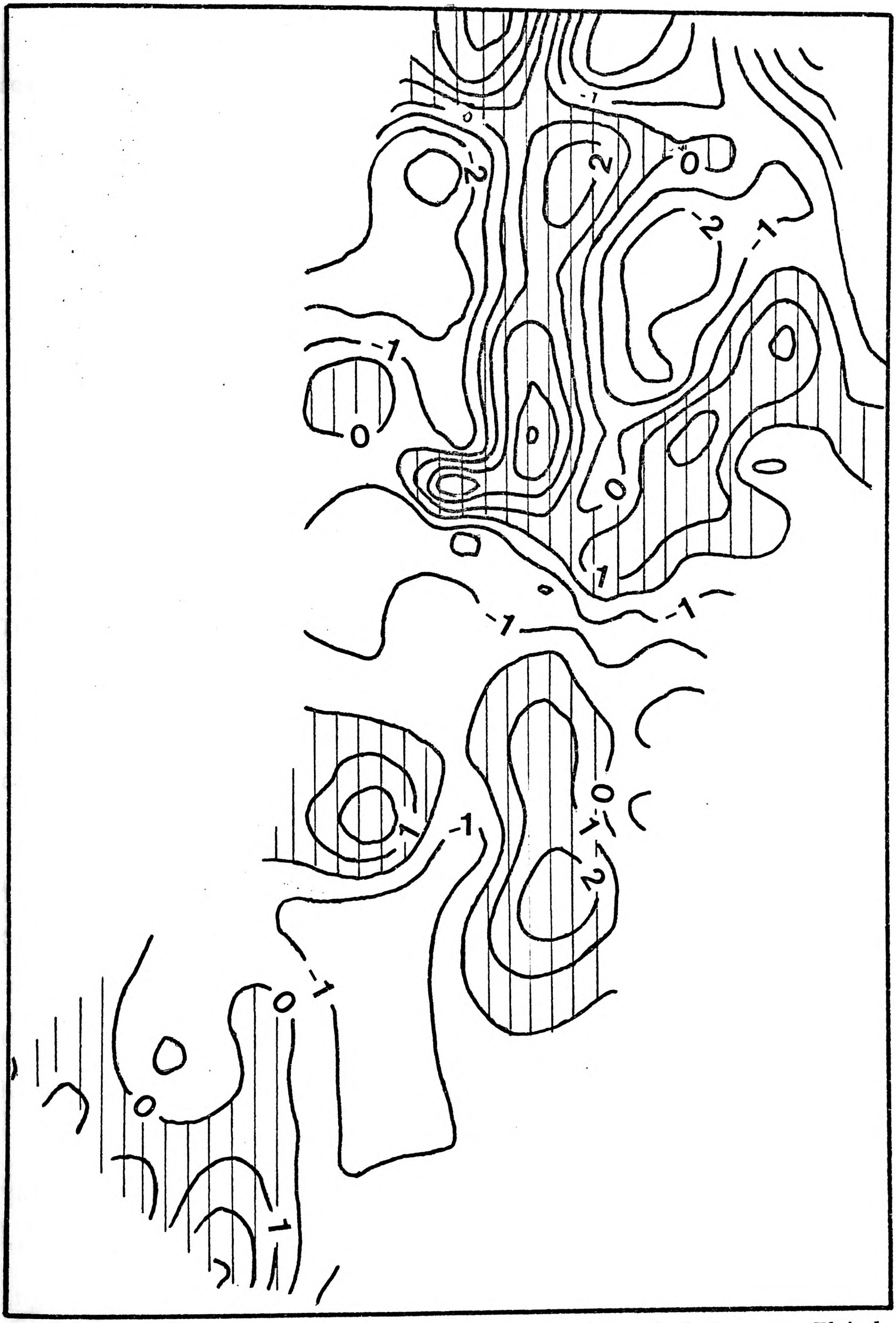


FIGURE 5.32 Mannering Park Claystone Mb - 2nd Degree Thickness Residuals

regional trends of the claystone to trends of other underlying units the local features appear to have a more complex relationship to the persistent local features in the thicknesses of other units and the present-day structure.

5.4.11 Wallarah Coal: Thickness

(a) Trend-Surfaces (Fig. 5.33)

All the trend-surfaces (Degree 1-4) fitted to the Wallarah Coal thickness data are significant absolutely and are significant improvements (based on F-tests at a 95% confidence level on all the terms and the added terms respectively, Table 5.1). Of all the formation thicknesses analysed, the Wallarah Coal thickness reported the highest proportion of the variation in the trend-surfaces at each corresponding degree of surface. Hence a large percentage of the variation

(66% for fourth degree trend) may be meaningfully expressed as a regression function. The residuals from the trend-surfaces are strongly autocorrelated and suggest that only a relatively small proportion of the total variation is random, with the local and regional variation components being very high.

The first degree trend-surface, accounting for 27% of the variation dips S 75 W and is a planar wedge thickening to the east. The surface is weighted in part by local rapid thickening in the northeast at Swansea and the deterioration in thickness over the Wyong Slope. The second degree trend is a

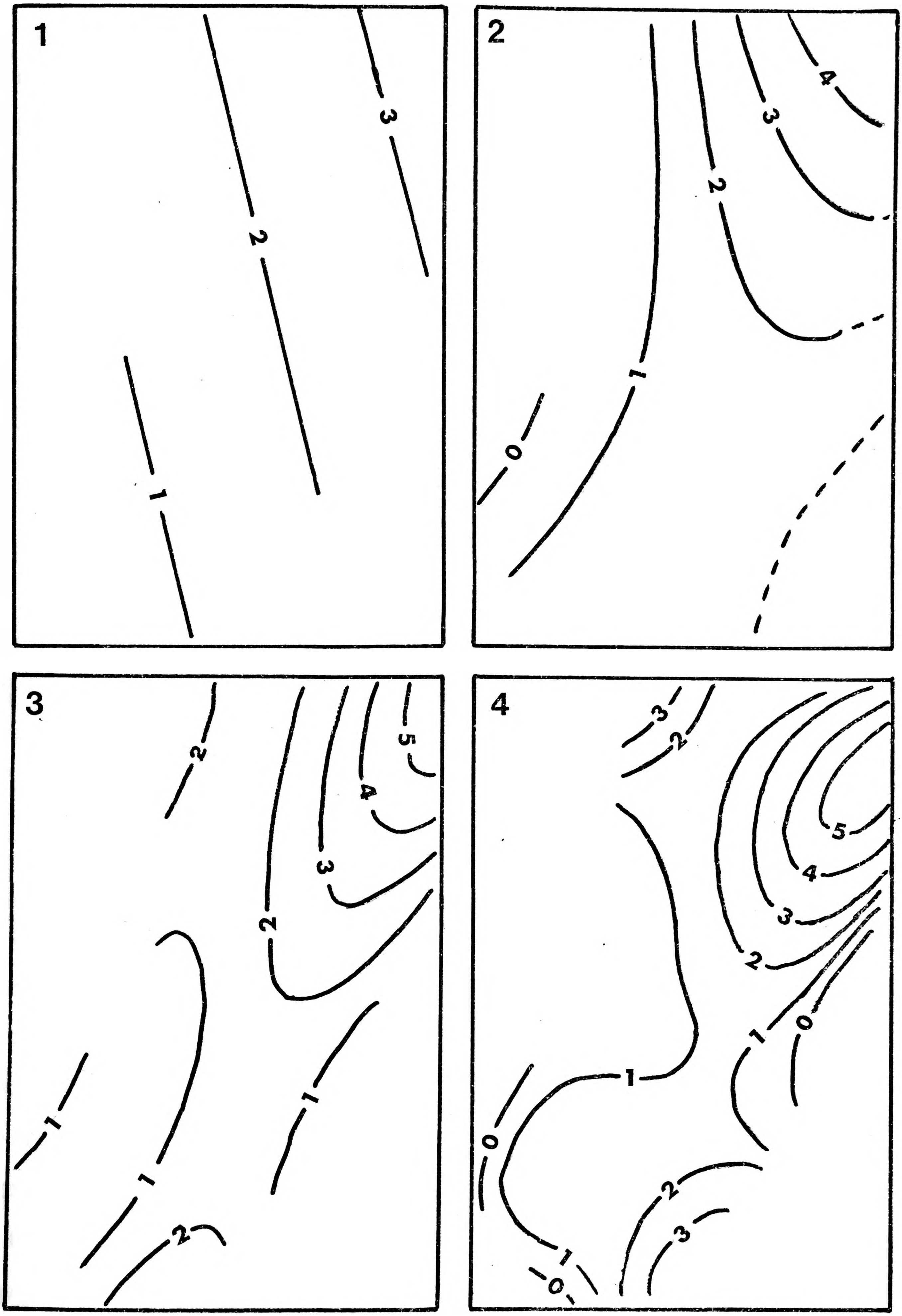


Fig.5.33.WALLARAH COAL - Thickness Trend-surfaces

Deg. 1-4

plunging antiform surface which thins to the west and south and whose major axis runs in a northeasterly direction (N 30 E) parallel to the axis of the Macquarie Syncline; it accounts for 37% of the variation. The third degree trend reveals a more detailed regional variation reflecting a close relationship with certain persistent features resolved in the analysis of some underlying units as well as with the present-day structure. A thickness trend maximum occurs in the northeast centred over the Chain Valley Depression; to the west is a narrow synform zone running along the Morisset Anticline and deflecting to the southeast along the Wyee Saddle. A regional trend minimum is indicated in the far southwest reflecting the rapid thinning of the Wallarah Coal over the Wyong Slope. The fourth degree trend shows a similar pattern of thickness variation to the third degree trend but is slightly more complex; it accounts for 66% of the variation.

Difference trend-surfaces are given in Fig. 5.34. Each of the difference surfaces represents significant proportions of the variation. The Degree 1-Degree 2 surface, isolating the second degree component, shows positive areas to the northeast and southwest with an intervening negative feature along the Morisset Anticline and the Wyee Saddle. The thickness maximum over the Chain Valley Depression is emphasised in the other difference maps which contain the third and fourth degree components. This positive zone is flanked to the east, west and south by positive areas coinciding with the main positive

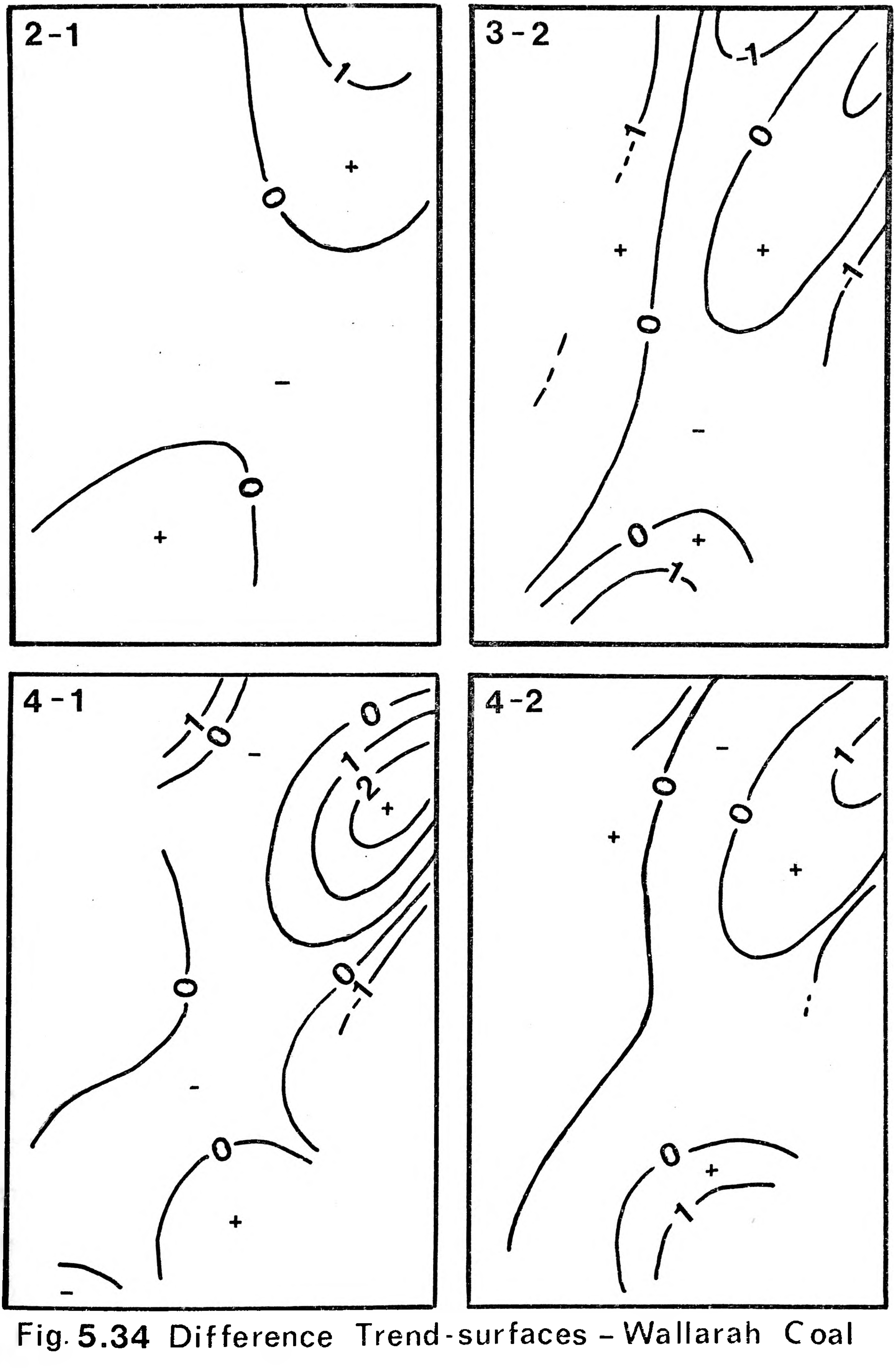


Fig. 5.34 Difference Trend-surfaces – Wallarah Coal Thickness

structural elements of the Macquarie Syncline area. In the far west adjacent to the Morisset Anticline is a zone of increasing thickness of the Wallarah Coal; this trend may partly be controlled by increased Permian subsidence over the area now manifest as the Yarramalong Syncline.

(b) Residuals (Fig. 5.35a,b,c)

Residual maps are presented for the second, third, fourth degree trend-surfaces to show the persistence of local features in the data even when a significant proportion of that variation is removed by the trend-surface. The second trend-surface is sufficiently complex to reveal the broad-scale regional variation component i.e., the antiform or synform thickness patterns along the Macquarie Syncline axis present in a number of the formations analysed especially the coals. The residuals from this surface reveal geographically extensive residual domains having a relatively simple configuration. A prominent positive thickness residual occurs over the Chain Valley Depression and corresponds with the area of maximum development of the Wallarah Coal. A negative domain to the west covers part of the area of the Morisset Anticline and extends south onto the Wyee Saddle. A small positive residual domain in the northwest is perhaps related to the structure-low area of the Yarramalong Syncline to the west. A positive residual domain occurs across the southern part of the Wyee Saddle and extends onto the Wyong Slope. This southern positive domain is an area of regionally thin coal; however

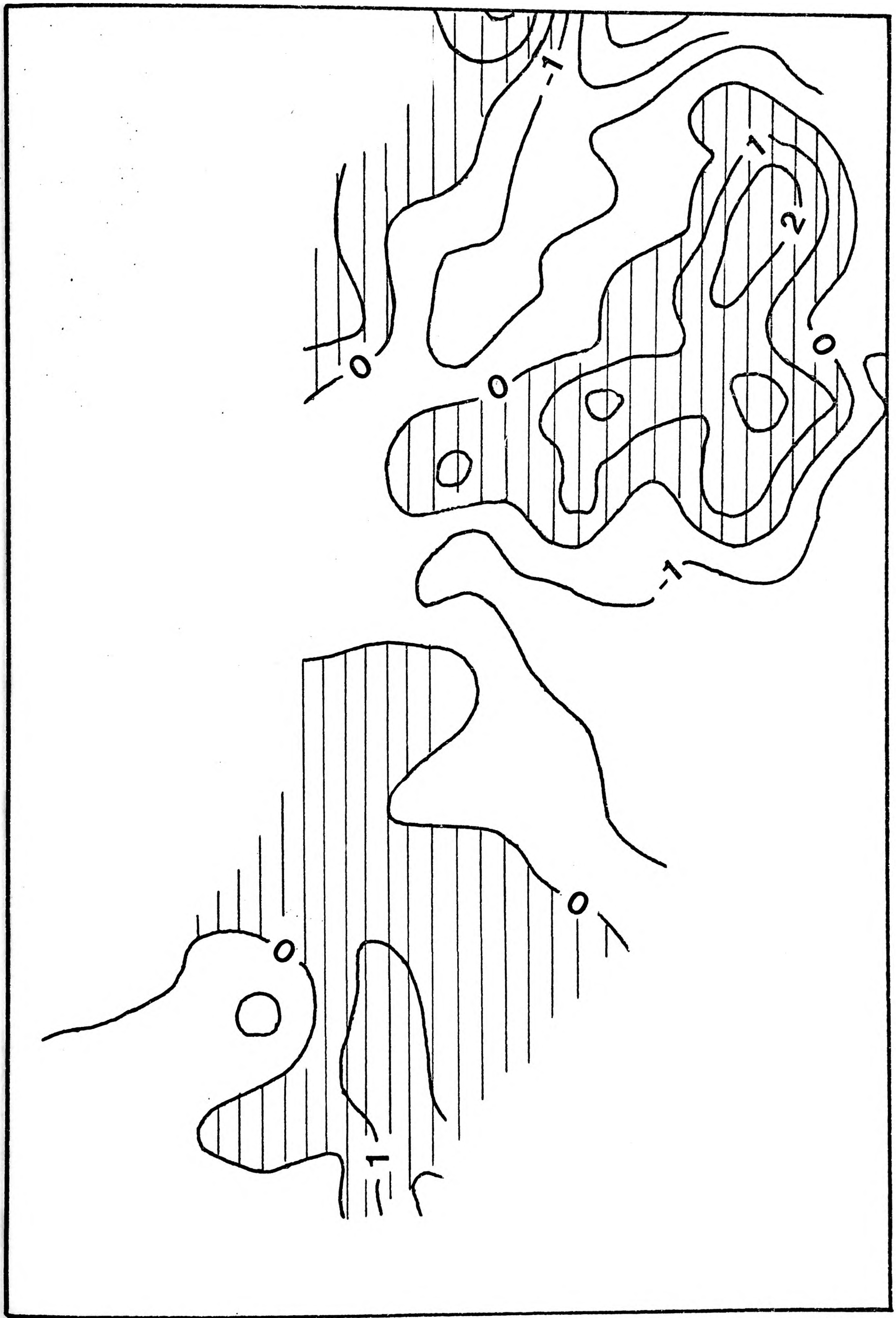


FIGURE 5.35a Wallarah Coal - 2nd Degree Thickness Residuals

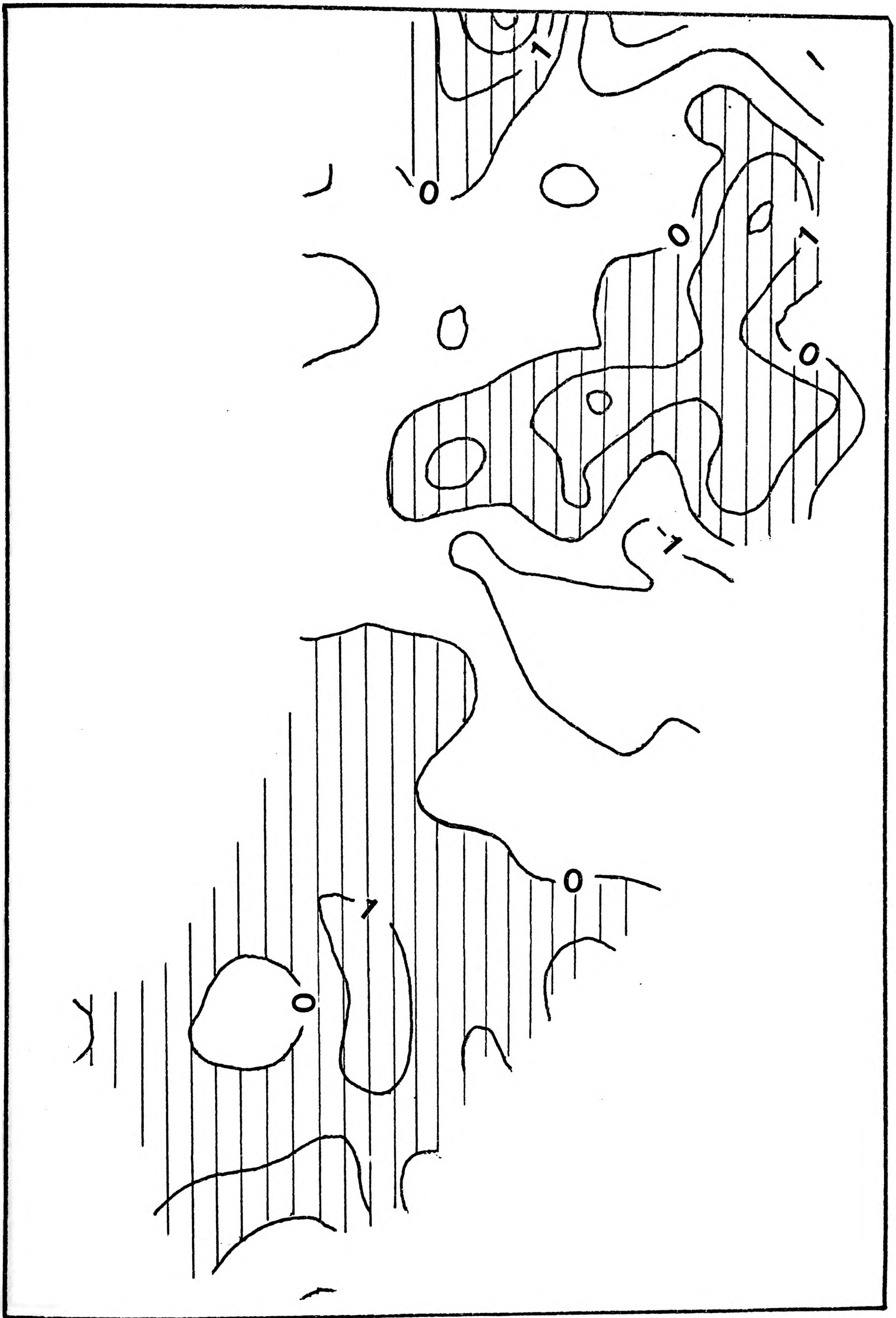
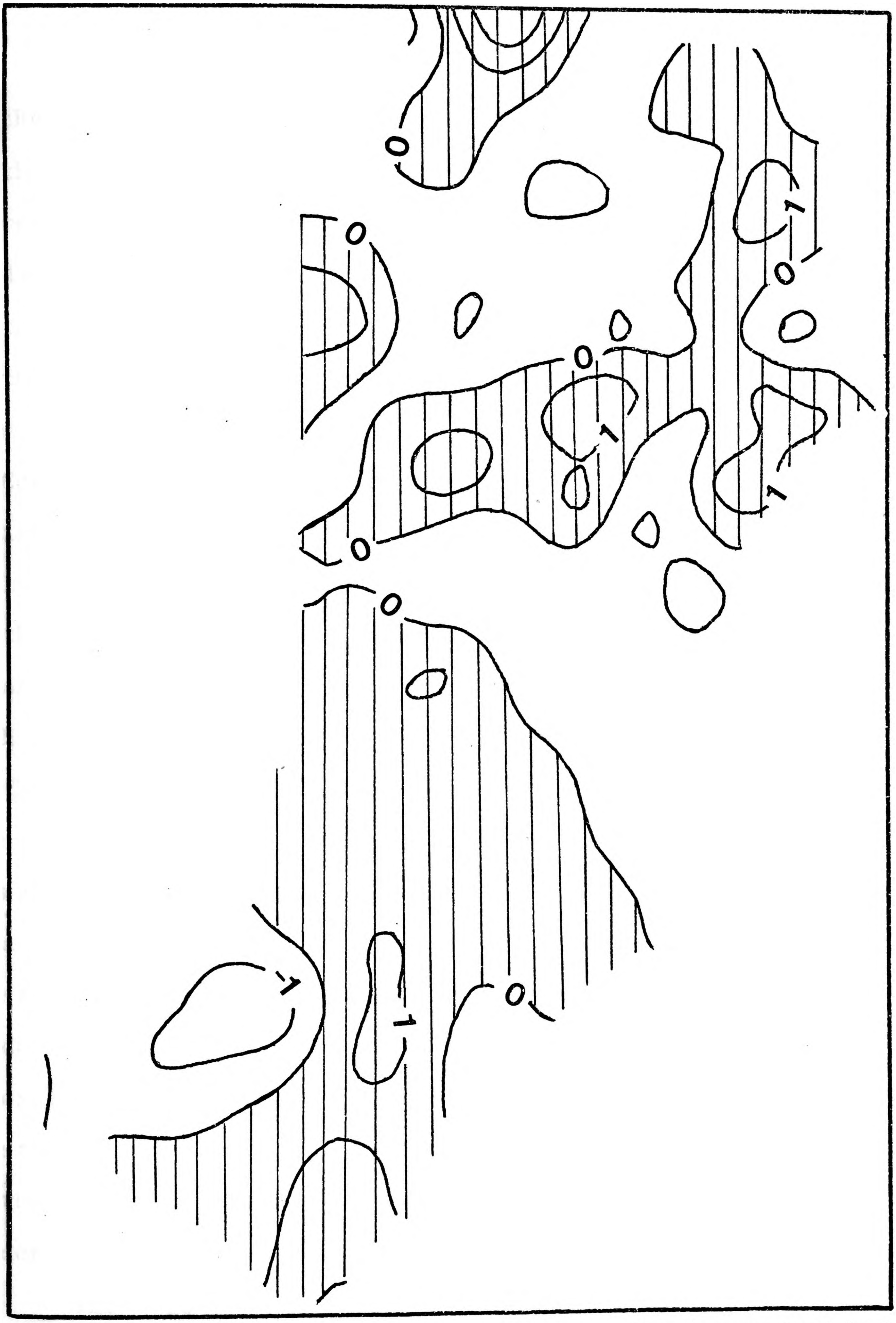


FIGURE 5.35b Wallarah Coal - 3rd Degree Thickness Residuals



<u>FIGURE 5.35c</u> Wallarah Coal - 4th Degree Thickness Residuals

the regional component is heavily influenced by the rapid thinning in the far south and the positive residuals are a result of the trend-surface being perturbed by the data. In the Wyong Slope area where the Wallarah Coal is less than 1m thick the residuals report as a negative domain. The thinning of the Wallarah Coal in the Wyong Slope area coincides with the sudden facies change and thinning of Teralba Conglomerate Mb. The poor development of the Wallarah Coal is probably related to the change in the thickness of the underlying formation. During the time of accumulation of peat of the Wallarah Coal water table conditions prevented or destroyed any organic accumulation. The water table may have been too high, the area being permanently flooded as a reflection of the thin outwash-phase of the Teralba Conglomerate, or alternatively the water table was too low and most organic debris was oxidised. The low water table may have been the result of a relatively lower rate of compaction subsidence of the thin sandstone than the dense, and very much thicker, conglomerate during the accumulation of the Wallarah Coal. The latter explanation is favoured as it is considered unlikely that standing bodies of water would have locally persisted during the period of extensive peat accumulation without substantial deposition of fine clastic sediments at that level.

The negative domain in the north is also relatable to residual features in the underlying units. It is a positive domain in the Mannering Park Claystone Mb. and a positive domain in the Teralba Conglomerate Mb. Similarly the northern negative zones in the Mannering Park Claystone Mb. and the Teralba Conglomerate Mb. roughly coincide with positive domains in the Wallarah Coal. However it is felt in these instances that differences in the development of the Wallarah Coal may be more attributable to contemporary structural subsidence patterns rather than differential compaction subsidence.

The residuals from the third and fourth degree trend-surfaces which account for a higher proportions of the thickness variation (48% and 66% respectively) both show residual domains geographically similar to those obtained from the second degree residuals, except that the amplitudes of the residuals for the higher degree residuals are slightly reduced. The persistence of the residual domains is a result of the high level of local autocorrelation and the relatively low variance of the thickness data of the Wallarah Coal. The relatively low variance is also reflected in the high degree trends which accommodate part of the local variation in the trend functions. The main modification in the pattern of residuals for the third and fourth degree trends is in the far south over the Wyong Slope where the trend-surfaces have flexed to fit the data of the thin Wallarah Coal. The negative thickness residual is reduced in area and confined to an area west of Wyong. The relatively high proportion of the variation explained by the trend-surfaces and the fact that each surface significantly improves the fit to the data is likewise a reflection of the low variance of the data and the lack of variation over the area of the variance itself.

5.4.12 Karignan Conglomerate Member and the Vales Point Coal Member: Thickness

The Karignan Conglomerate Member and the Vales Point Coal Member are more restricted in their geographic extent than the lenticular coal units in the Teralba Conglomerate Mb. and as a result they are considered to be of limited value in illustrating regional controls on their deposition. However their trend-surfaces (Fig. 5.36, and Fig. 5.38) still show trends not unlike those observed in some lower units. The development of these two formations is apparently related to local features in the area being confined to the area of the Chain Valley Depression and not extending south across and apparently confined by the Wyee Saddle structure. Also their axes of development run NNE along the axial line of the Macquarie Syncline. The residuals from the second degree trend for the thickness of the Karignan Conglomerate Mb. and from the third degree of the thickness of the Vales Point Coal Mb. are given in Fig. 5.37 and Fig. 5.39 respectively. However no obvious relationships with the residuals of other formations are detectable.

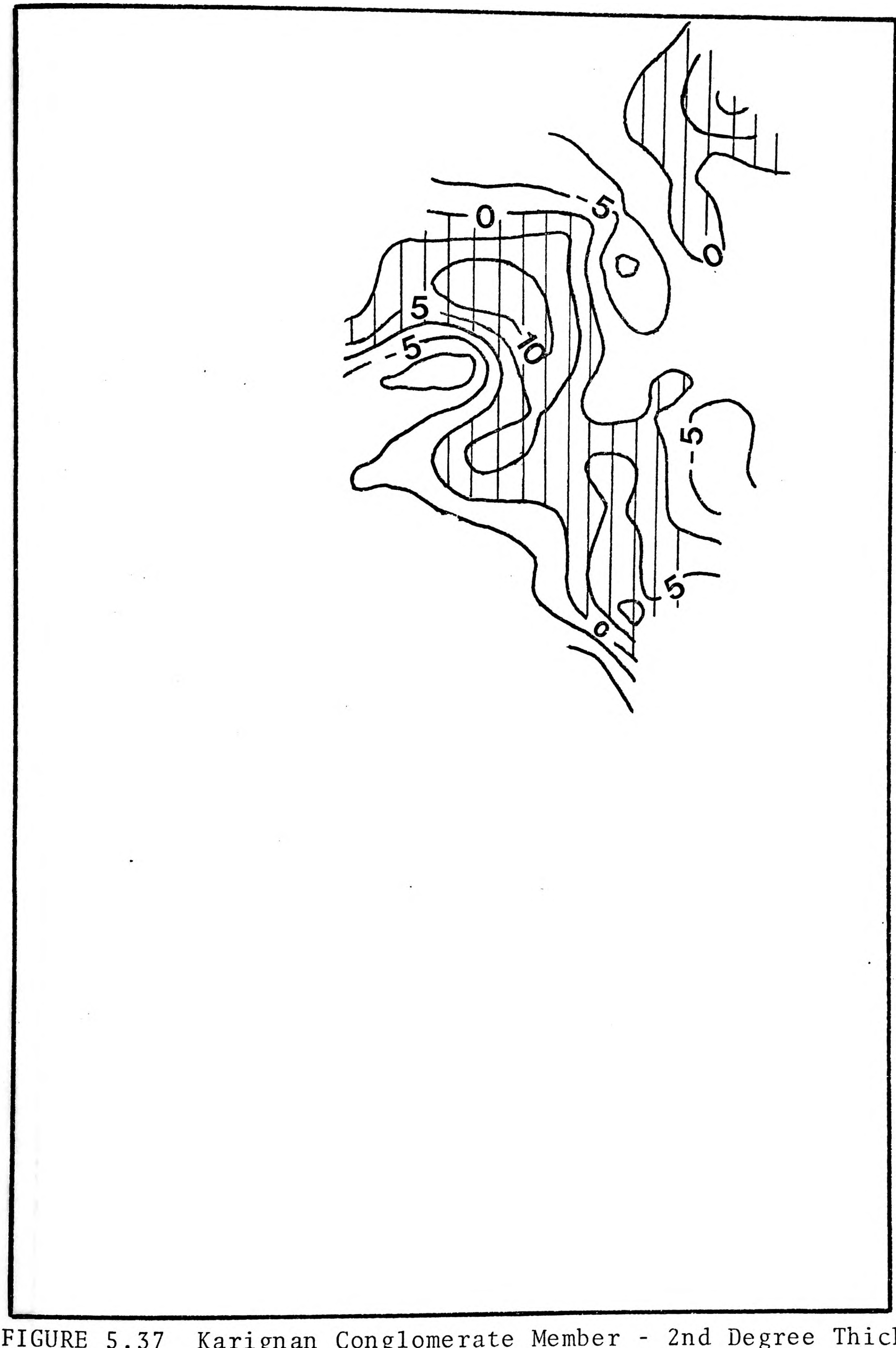


FIGURE 5.37 Karignan Conglomerate Member - 2nd Degree Thickness Residuals

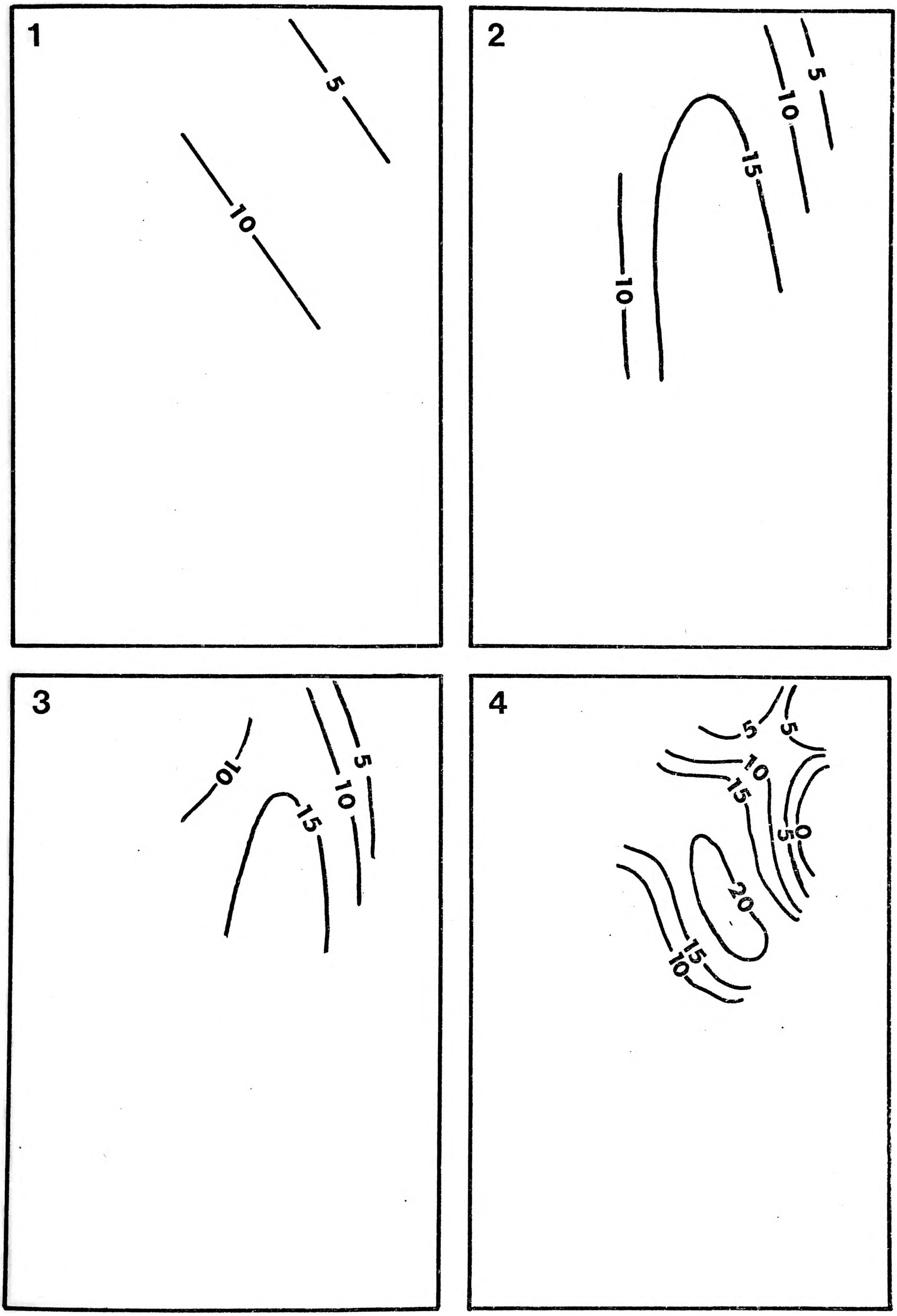


Fig.5.36.KARIGNAN CONGLOMERATE MEMBER-

Thickness Trend-surfaces Deg. 1-4

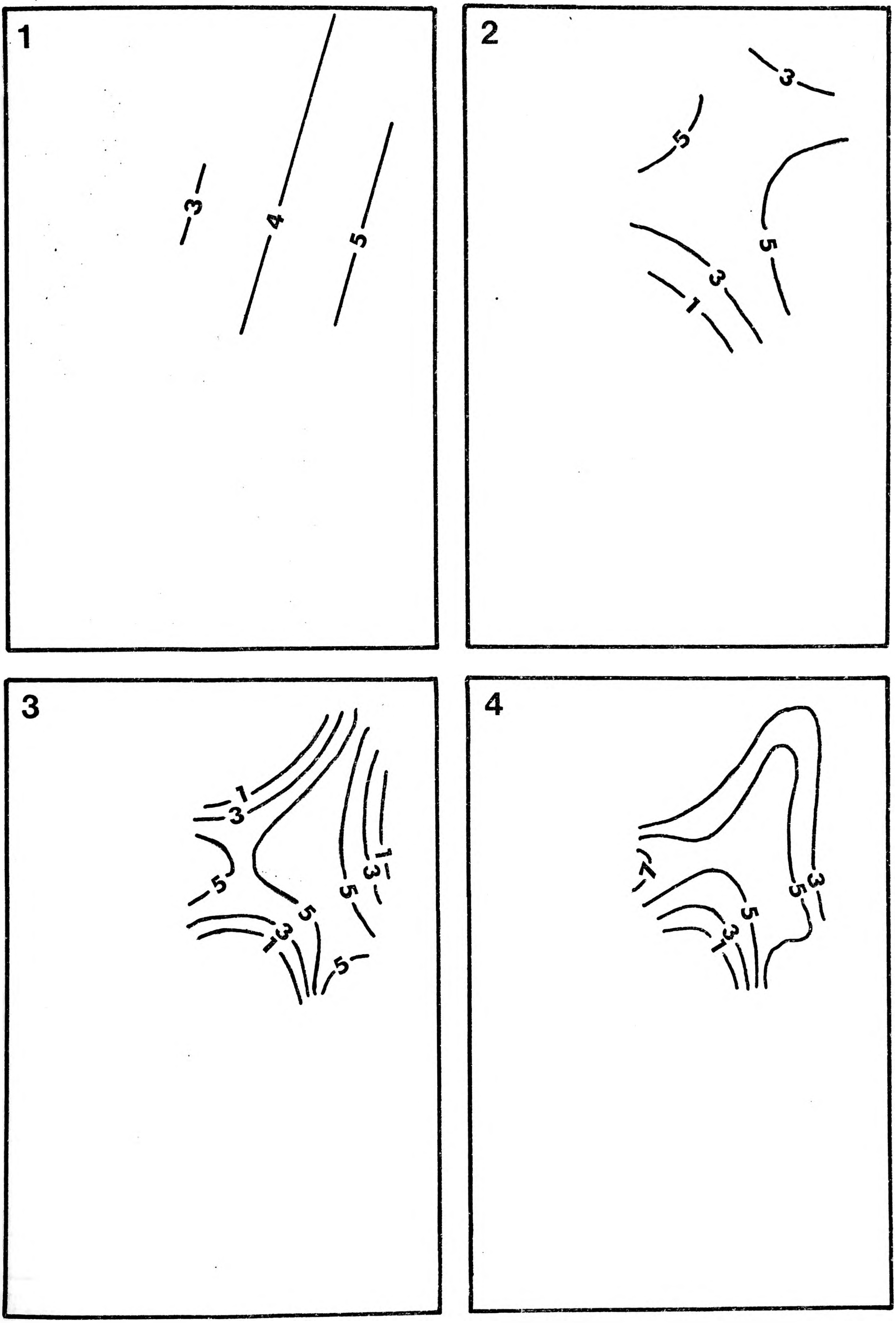


Fig.5.38.VALES POINT COAL MEMBER – Thickness

Trend-surfaces Deg. 1–4

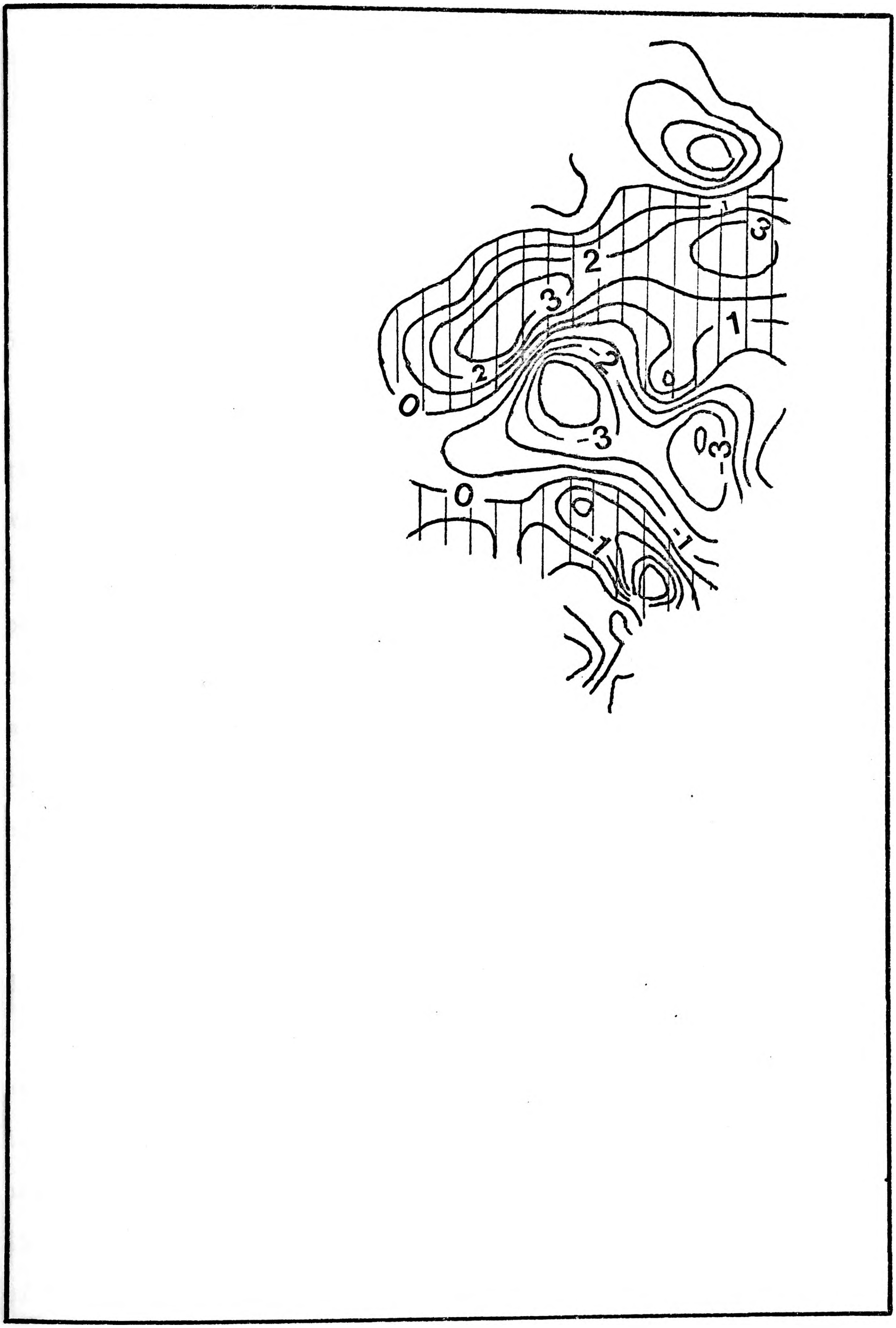


FIGURE 5.39 Vales Point Coal Member - 3rd Degree Thickness Residuals

CHAPTER 6

REVIEW AND COMPARISON OF THE TREND-SURFACE ANALYSIS RESULTS FOR STRUCTURE AND THICKNESS VARIABLES

6.1 PRESENT-DAY STRUCTURE OF THE M.I.B.: TREND-SURFACES AND RESIDUALS

The results of the trend analysis of the structure of the (South) Fassifern Coal, the Great Northern Coal and the Wallarah Coal were very similar in that the geometries of the trend-surfaces and the geographic distribution of the positive and negative residuals remained almost constant for each formation. Slight differences are attributable to minor variations in the total thickness of the M.I.B. but these are insufficient to influence the regional structure of units at the base, relative to units at the top of the M.I.B. Residual patterns are only locally affected by thickness differences such as that caused by the restricted distribution of conglomerate within the Doyalson Formation.

On the basis of the trend-surface analyses regional and local components in the structure of the M.I.B. can be identified. At the scale of the Sydney Basin a regional homoclinal dip component, dipping southwest at approximately 15 m per kilometre towards the present-day structural centre of the basin, may be identified from the linear structure trend-surfaces of the widespread formations in the M.I.B.

A regional synclinal component, corresponding with the Macquarie Syncline, and superimposed on the homoclinal dip, is present in the second degree structure trend-surfaces.

While trend-surfaces are intended to represent regional variations in the data, high degree trend-surfaces increasingly approach total trend-surfaces (as described in Sections 3.3.4) and with data which shows a high level of serial auto-correlation there is a tendency to include local features (i.e., those features that do not extend over the entire map area) in the trend-surface. Thus the third and fourth degree structure trend-surfaces not only give a more detailed resolution of the regional structure but also include part of the local variation in the surfaces. Although residuals from the higher degree surfaces may still represent local features there is an effective reduction of scale in terms of the regional components in relation to the overall regional structure of the basin. The complexity of trend-surfaces over small areas of the Sydney Basin must be related to the complexity of the regional basin structure if the structural features (both regional and local) in the sub-basin areas are to be considered geologically relevant samples of the basin structure.

While the degree 3 and 4 surfaces improve the fit it is felt that the additional variation explained (approx. 5% in most units) is part of the local structural variation. Consequently the second degree structure trend-surfaces are adopted as adequate representations of the present-day regional structure.

Local structural features have been defined on the basis of the residual domains outlined in the trend-surface analysis. Positive local structures are the Morisset Anticline, the Swansea Rise, and the Wyee Saddle (*vide* Figs. 5.3 and 6.1). Negative local structures are the Chain Valley Depression and the Wyong Slope, both located along the axial zone of the Macquarie Syncline. Although part of the variation associated with the local structures (with the possible exception of the Wyee Saddle) may be represented in the second degree trend-surfaces, the features defined on the basis of their residual domains will be locally auto-correlated extrema of residuals and hence reliable local components of the variation.

6.2 THICKNESS VARIATIONS OF UNITS IN THE M.I.B.: TREND-SURFACES AND RESIDUALS

The usefulness and geological significance of the results of the trend-surface analyses of the successive formations of the M.I.B. is apparently dependent on the geographic extent, the lithology and the time over which the particular formation accumulated. Broadly the formations analysed may be grouped into four main groups on the basis of their lithologies and their geographic extent:

(a) Coaly units of restricted extent.

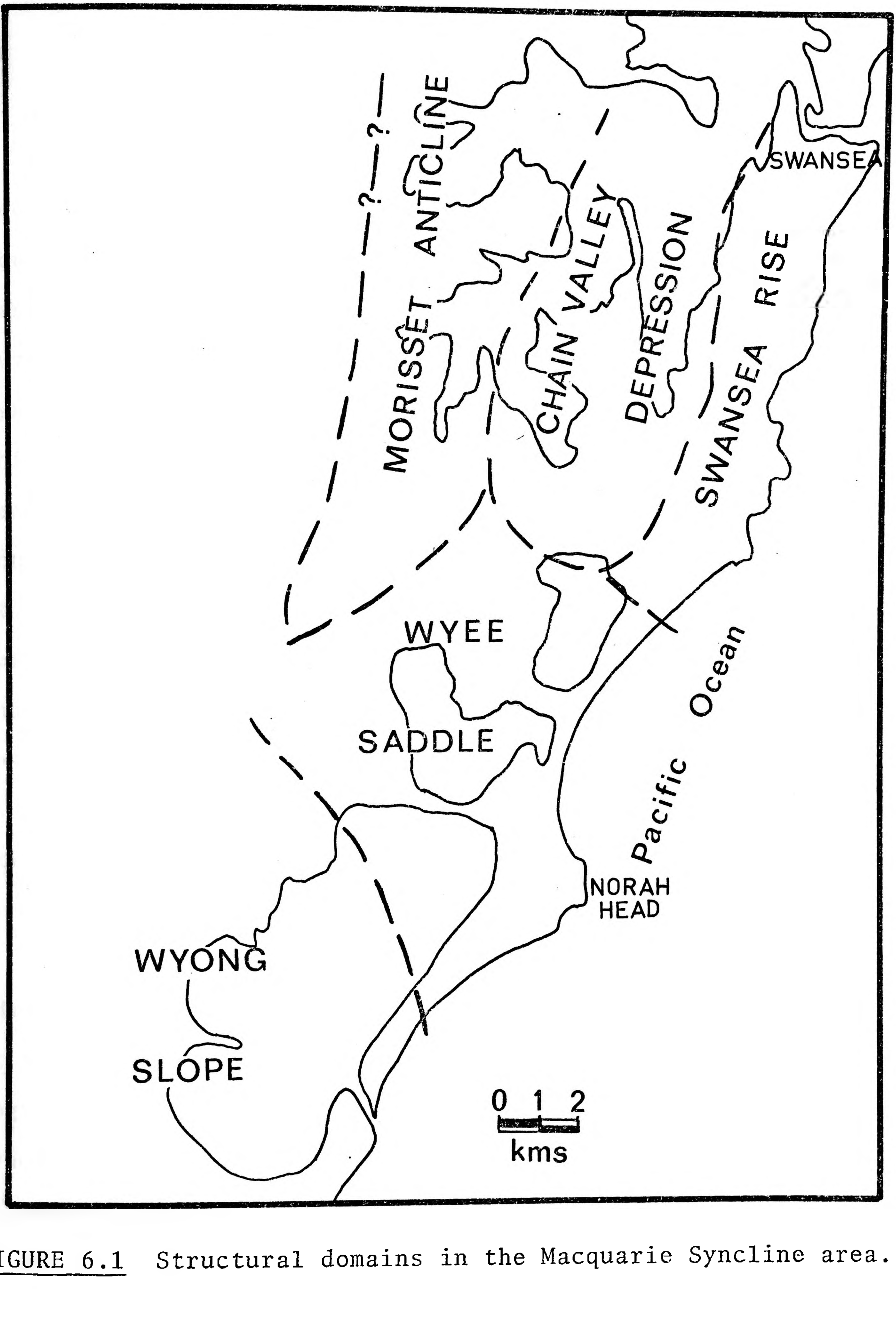


FIGURE 6.1 Structural domains in the Macquarie Syncline area.

(b) Widespread fine clastic units.

(c) Widespread coarse clastic formations.

(d) Widespread coal formations.

The results for the restricted units, which include the Toukley Coal Lens, the Buff Point Coal Lens, and the Tangy Dangy Coal Member, are of limited value in that their trend-surfaces are more related to local features in the Macquarie Syncline than to regional trends. The geometries of the thickness trends of these units do not appear to reflect meaningful or persistent patterns of development in the context of the present study. Likewise the residuals, being at a different level of complexity to the local features defined for the widespread units, are difficult to interpret and relate to residuals of other units. The only common observation that can be made on the restricted coal units is that they tend to have an elongate development along the axis of the Macquarie Syncline and are related to the structure-low parts of the area.

Thickness trend-surfaces of the fine clastic units (Mannering Park Claystone Mb., Fig. 5.30; and the claystone at the top of the Doyalson Formation, Fig. 5.15) reveal regional antiform thickness patterns along the Macquarie Syncline axial zone and show an overall linear increase in thickness to the north. Residuals for both claystone units to some extent, albeit weakly, have an inverse correspondence with the present-day local structures, i.e., positive thickness residuals occur over negative structure residuals and the reverse also holds.

Coarse clastic units, which volumetrically form the bulk of the sediments within the M.I.B., do not show consistent regional thickness trends. The Doyalson Formation (Fig. 5.13) has a synform trend along the Macquarie Syncline axis thickening to the east and west and also to the south. The Teralba Conglomerate Mb. regional thickness trends (Fig. 5.24) cannot be directly related to the thickness trends of other units nor to present-day structure features. The positive residuals for the Teralba Conglomerate Mb. (Fig. 5.26) tend to occur along the present-day structure high areas. However, as pointed out above (Section 5.3.8), there may be a reversal of relative thickness patterns of the Teralba Conglomerate Mb. This reversal may be caused by differential compaction of the restricted coal lenses where these are included in the Teralba Conglomerate Mb. The thickness variations of both the Teralba Conglomerate Mb. and the Doyalson Formation appear to be more controlled by local sedimentological influences including the nature and competence of the underlying peat horizons (which, in turn, may have affected channel directions and grain size variations). The Eleebana Formation is the only clastic formation in the M.I.B. showing significant lateral facies variation; lithologies include fine conglomerate, sandstone and claystone. Perhaps as a consequence of subsequent differential compaction of these lithologies, the regional thickness trends (Fig. 5.18) are relatively complex, even though an antiform pattern parallel to the Macquarie Syncline axis is present in the second degree trends. Residuals (Fig. 5.20) from the high degree trends tend to show an inverse relation with present-day structure residuals although thickness residuals from the low degree surfaces appear more haphazard.

The three widespread coal formations of the M.I.B. yielded very consistent trend-surface analysis results. The Wallarah Coal (Fig. 5.33), the Great Northern Coal (Fig. 5.21), and the Fassifern and South Fassifern Coal (Fig. 5.10) all show antiform thickness trends parallel and coincidental to the regional structure trends and the Macquarie Syncline. However, the Wallarah Coal and the (South) Fassifern Coal thickness trends have a plunge component (see Fig. 6.2) to the southwest (i.e., thickening to the northeast) while the Great Northern Coal has a plunge component to the northeast. While the linear components may be caused by a planar regional subsidence pattern they may also be explained by local biased sampling of extrema at the northern and southern ends of the area, especially in the case of the Great Northern Coal which is locally thin in the north and locally thick in the far south. These local extrema may be caused by relative differences in subsidence due to compaction of the underlying

Eleebana Formation which is coarse-grained where the Great Northern Coal is thin and fine-grained in the far south where the coal is thick.

Local thickness variations of the Wallarah Coal (Fig. 5.35) and the Fassifern and South Fassifern Coal (Fig. 5.12) show a relatively strong complimentary relation to the present-day structure residuals (i.e., positive thickness residuals occur over negative structure residuals and *vice versa*). Although the local variations in the thickness of the Great Northern Coal (Fig. 5.23) to some degree coincide with present-day local structural features, the geography of the residual thickness domains is also influenced by other extraneous factors perhaps controlled by the competence of the underlying lithology or erosional effects of the overlying conglomerate.

In order to clarify the apparent relationships between regional and local thickness variations of successive formations and between these variations and the present-day structure the trend and residual thicknesses have been classified and compared to the present-day structure.

6.2.1 Thickness Trend-Surfaces

The main directional features of the seven major units which show statistically significant trends are given in Fig. 6.2. For the first degree trends the directions plotted are the direction of maximum decrease in thickness (similar to the 'dip' directions given in Chapter 5), while for the higher degree trends the axes of the surfaces are given; in all cases the arrows point in the direction of decreasing thickness. The axes of the structure trend-surfaces for the Wallarah Coal are given for comparison; arrows indicate increasing depth.

The directions of the first degree thickness trends can be effectively considered as resultants of the two axial directions for the second degree surfaces which suggests that the level of variation across the Macquarie Syncline approaches that along the axis of the Syncline. Table 6.1 shows the coefficients of determination for the formations given in Fig. 6.2 associated with the planar thickness component (along the axis), the pure synform component, and the local and random component of the variation. For the coals the variation associated with the planar thickness component is greater than the variation associated with the synform component. Coefficients of determination for the clastic horizons show that the synform component varies from a small fraction of the planar variation (Eleebana Formation) to a level slightly greater than that accounted for by the planar thickness component.

The thickness axes of the third and fourth degree trends tend to characterise features which partly include variation components associated with local features in the data (Fig.

VARIABLE	COMPONENT			
	Deg. 1 (Planar)	Deg. 2-1 (Synclinal)	Deg. 4-2	Residual 4 (Local)
Wallarah (Structure)	0.81	0.12	0.05	0.02
(THICKNESS)				
Wallarah Coal	0.27	0.10	0.29	0.34
Mannering Pk Clayst. Mb.	0.14	0.17	0.07	0.76
Teralba Congl. Mb.	0.18	0.22	0.14	0.46
Great Northern Coal	0.23	0.07	0.30	0.40
Eleebana Fm.	0.22	0.04	0.13	0.61
Doyalson Fm.	0.27	0.15	0.09	0.49
(Sth) Fassifern Coal	0.06	0.05	0.12	0.77

TABLE 6.1 Coefficients of determination for components of variation of formations given in Fig. 6.2.

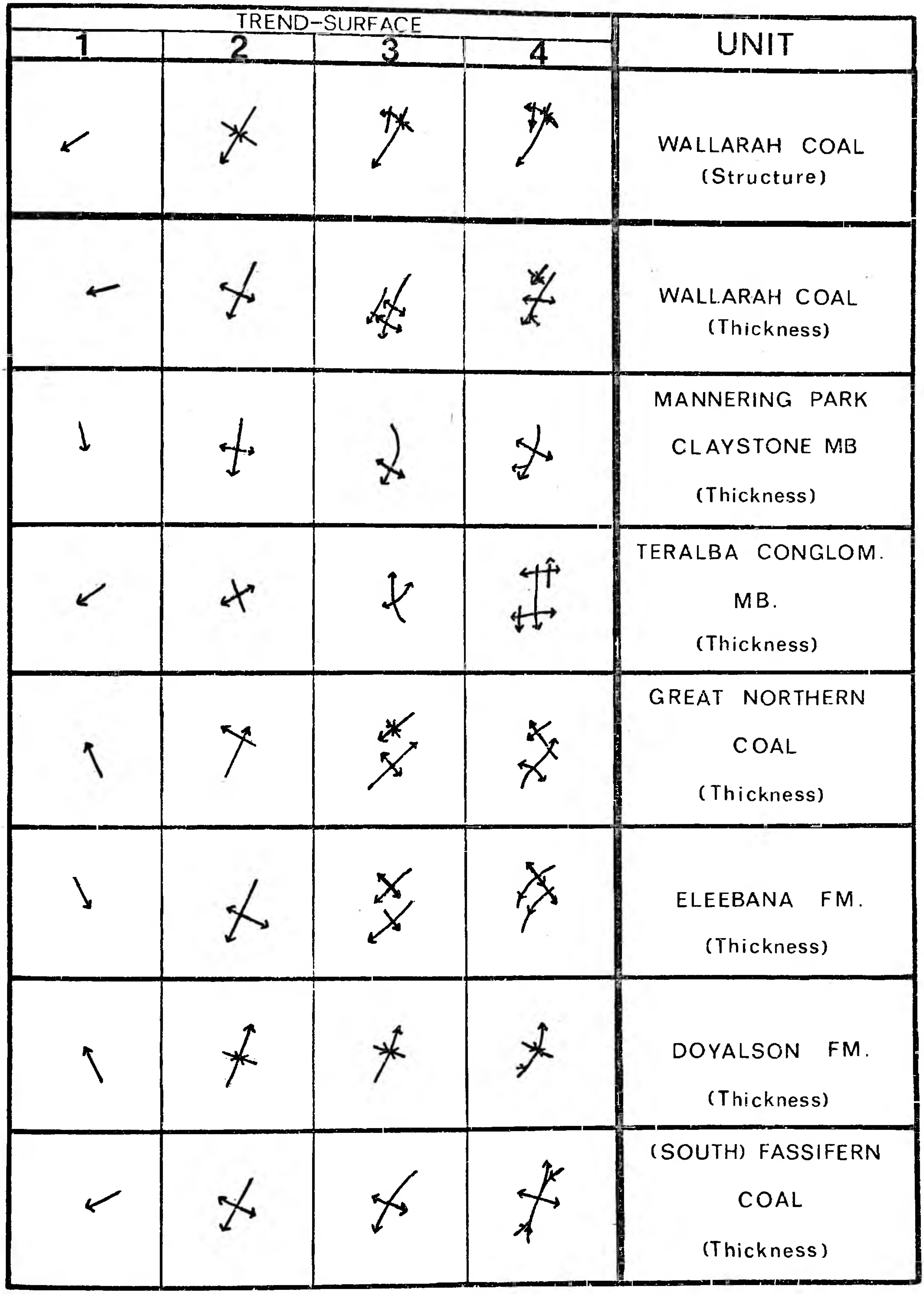


FIGURE 6.2 Directional axes of structure and thickness trend-surfaces

6.2 and Table 6.1).

As can be seen from Fig. 6.2 all the formations which show statistically significant trends, with the exception of the Teralba Conglomerate Mb., have their second degree thickness axes parallel to the second degree regional structure axes. Of these the (South) Fassifern Coal, the Eleebana Formation, the Mannering Park Claystone Mb. and the Wallarah Coal indicated regional thickening to the north along their major axes and a regional thickening from the east and west in towards the major axes. The major axes of the thickness trends for these formations all strike approximately northeast parallel to the second degree structure axis; all except the Eleebana Formation are coincident with the Macquarie Syncline axis.

The Doyalson Formation and the Great Northern Coal both have thickness axes similar in direction but of opposite sense to the axes of the units described above. Weighting of the trend-surfaces by local extrema is the likely cause of the southerly increase in thickness of the Great Northern Coal. The rapid thinning of the Doyalson Formation in the north of the area may be responsible for the linear dip component of the thickness trend-surfaces rather than an overall regional thickening to the south. The thickness trends for the Great Northern Coal, although partly reflecting a common regional structural control, appear more closely related to the thickness trends of the Eleebana Formation.

This relationship is suggested by the third degree trend axes of both formations (see Fig. 6.2) which reveal a very close inverse and complimentary pattern of development. As mentioned above the thickness variation of the Eleebana Formation is partly associated with its lithological variation and hence in the case of the Great Northern Coal there is a substantial influence on its thickness by the nature of the underlying lithology.

The Teralba Conglomerate Mb. has not resolved into regional thickness patterns consistent with results of other formations of the M.I.B. Axes of thickness are not parallel to the other regional trend-surface axes. It can therefore be argued that the development of the Teralba Conglomerate Mb. has not been controlled by regional variations in tectonic subsidence.

On a regional scale the thickness trends generally suggest the existence and influence of a persistent regional, differential tectonic subsidence pattern. Structural subsidence was greatest along a northeasterly axis through the area; the probable regional subsidence axis coincides with the present-day Macquarie Syncline axis. Although a certain degree of contradiction is present in the linear components of the thickness variations it would appear that there was a slight homoclinal subsidence pattern to the northnortheast along the axis of the more dominant "synclinal" subsidence. Hence while the fold component of the Macquarie

Syncline may be considered as an intensification of a pre-existing Permian subsidence pattern the present-day homoclinal dip is probably due to some subsequent deformation unrelated to the Upper Permian tectonic subsidence.

6.2.2 Classification of True Thicknesses and Residual Thicknesses

In order to examine quantitatively the thickness data for relationships between individual units, correlation matrices for the raw thicknesses and the residuals of each thickness trend-surface for each formation studied were calculated. These matrices are given in Table 6.2; all data were standardised prior to computation of the correlation matrices. From the five correlation matrices cluster diagrams were constructed using a program modified and adapted after McCammon (1970). The resultant dendrographs for the raw thickness data correlation matrix and the second degree residual thickness correlation matrix are given in Fig. 6.3a, 6.3b.

The data clustered at fairly low levels of similarity and according to McCammon (1968) clustering below similarity levels of 0.2 should be ignored. From the structure of the dendrographs it would appear that many of the correlations between a number of formations are casual rather than causal. All but one of the cluster groups contained formations which were not directly associated stratigraphically and from

Vales Pt Coal Lens	1.00													
Karignan Congl. Mb	0.18	1.00												
Wallarah Coal	0.01	*-0.25*	1.00											
Mannering Pk C'lst.	-0.10	0.15	*0.20*	1.00										
Toukley Coal Lens	-0.20	-0.17	-0.24	0.05	1.00									
Buff Pt Coal Lens	-0.12	*-0.42*	-0.34	-0.18	0.08	1.00								
Teralba Cong. Mb.	0.05	0.13	-0.05	0.02	0.15	*0.28*	1.00							
C'lst Roof	*0.43*	0.17	-0.02	0.14	0.01	*-0.59*	-0.19	1.00						
Great Nthn Coal	0.10	0.09	*-0.19*	*-0.20*	-0.15	0.03	*-0.35*	0.08	1.00					
Eleebana Fm.	-0.09	-0.10	*0.28*	0.06	0.23	-0.30	0.06	0.14	*-0.33*	1.00				
Chain V'y Coal	*-0.21*	*-0.35*	*0.25*	-0.04	0.14	-0.31	0.03	-0.20	-0.14	*0.27*	1.00			
C'lst Floor	0.25	0.19	0.09	*0.31*	-0.29	-0.21	-0.06	*0.24*	-0.06	-0.07	0.09	1.00		
Doyalson Fm.	0.03	-0.17	*-0.25*	*-0.17*	-0.06	0.14	-0.38	*-0.56*	0.10	*-0.66*	-0.06	-0.08	1.00	
(Sth) Fassifern Coal	0.29	0.09	*0.23*	0.13	-0.02	-0.31	0.09	0.24	-0.16	0.15	0.04	0.22	-0.11	1.

TABLE 6.2a Correlation matrix for raw thicknesses (values in italics significant at 95% confidence interval; note that correlation coefficient calculated for different numbers of sample points).

Vales Pt Coal Lens	1.00				
Karignan Congl. Mb	0.23	1.00			
Wallarah Coal	0.06	-0.11	1.00		
Mannering Pk C'1st.	0.07	0.18	0.09	1.00	
Toukley Coal Lens	0.16	-0.21	-0.09	0.12	1.00
Buff Pt Coal Lens	0.18	*-0.45*	-0.25	-0.03	*0.45*
Teralba Cong. Mb.	0.10	0.11	*-0.34*	-0.13	0.18
C'1st. Roof	0.36	*0.37*	*-0.32*	-0.06	-0.06
Great Nthn Coal	0.05	*0.20*	-0.06	0.03	0.01
Eleebana Fm.	0.06	-0.13	*0.21*	-0.15	0.13
Chain V'y Coal	0.23	-0.33	*0.21*	-0.08	0.04
C'1st Floor	0.16	0.18	-0.02	*0.29*	-0.15
Doyalson Fm.	0.00	*-0.35*	-0.03	-0.05	-0.01
(Sth) Fassifern Coal	0.28	0.19	*0.17*	0.08	-0.07

TABLE 6.2b Correlation Matrix for 1st

1.00								
0.27	1.00							
-*0.66*	-0.13	1.00						
-0.16	-*0.26*	0.24	1.00					
-0.18	-0.11	0.10	-0.15	1.00				
-*0.21*	-0.05	-0.11	-0.05	0.19	1.00			
-0.24	-0.24	0.06	0.05	-0.15	0.09	1.00		
-0.12	-*0.23*	-0.51	-0.19	-*0.52*	0.07	0.02	1.00	
-0.22	0.03	0.21	-0.10	0.10	0.01	0.17	0.01	1.

Degree thickness residuals.

Vales Pt Coal Lens	1.00				
Karignan Congl. Mb.	0.19	1.00			
Wallarah Coal	0.14	0.03	1.00		
Mannering Pk C'1st.	0.14	0.11	0.08	1.00	
Toukley Coal Lens	0.12	-0.19	-0.19	0.12	1.00
Buff Pt Coal Lens	0.03	-0.49	-0.26	-0.07	0.53
Teralby Cong. Mb.	0.09	-0.03	*-0.26*	*-0.22*	0.22
C'1st. Roof	0.32	0.23	-0.25	0.08	0.00-
Great Nthn Coal	0.08	*0.30*	*-0.21*	0.06	0.03-
Eleebana Fm.	0.01	-0.02	*0.19*	*-0.18*	0.11-
Chain V'y Coal	0.21	*-0.34*	*0.20*	-0.10	0.01-
C'1st Floor	0.07	0.16	-0.02	*0.25*	-0.11-
Doyalson Fm.	0.09	*-0.24*	0.15	0.03	-0.11
(Sth) Fassifern Coal	0.14	0.14	0.10	0.05	-0.07-

<u>TABLE 6.2c</u> Correlation matrix for 2nd

1.00								
0.25	1.00							
-*0.57*	-0.11	1.00						
-0.09	-0.08	0.19	1.00					
-0.28	-*0.19*	0.23	-*0.17*	1.00				
-0.18	-0.09	-0.19	-0.05	0.16	1.00			
-0.48	-0.31	0.02	-0.05	-0.12	0.09	1.00		
0.03	-0.19	-0.53	-*0.21*	-*0.52*	0.15	0.06	1.00	
-0.17	0.05	0.25	-*0.17*	0.06	-0.01	0.14	0.06	1.00

Degree thickness residuals.

Vales Pt Coal Lens	1.00													
Karignan Congl. Mb.	0.07	1.00												
Wallarah Coal	0.14	0.00	1.00											
Mannering Pk C'lst.	0.16	0.11	0.11	1.00										
Toukley Coal Lens	0.17	-0.19	-0.18	0.20	1.00									
Buff Pt Coal Lens	0.08	-0.46	-0.14	-0.02	*0.55*	1.00								
Teralba Cong. Mb.	0.17	-0.02	-*0.17*	-*0.29*	0.22	0.17	1.00							
C'lst. Roof	0.33	0.17	-0.16	-0.11	-0.10	-0.66	-0.12	1.00						
Great Nthn Coal	0.15	*0.34*	-*0.28*	-0.01	-0.05	-0.22	-0.10	0.08	1.00					
Eleebana Fm.	0.02	-0.04	*0.20*	-0.13	0.06	-0.15	-*0.19*	0.25	0.01	1.00				
Chain V'y Coal	0.10	-0.38	0.18	-0.15	0.04	-0.24	-0.07	-0.07	-0.04	*0.23*	1.00			
C'lst Floor	0.12	0.06	-0.07	0.20	-0.13	-0.49	-*0.34*	-0.02	-0.02	-0.08	0.03	1.00		
Doyalson Fm.	0.02	-0.28	0.12	0.03	-0.00	-0.05	-0.16	-0.47	-*0.21*	-*0.56*	0.16	0.05	1.00	
(Sth) Fassifern Coal	0.08	0.12	0.10	0.07	0.01	-0.19	0.06	0.20	-*0.18*	0.04	-0.08	0.10	0.04	1.00

TABLE 6.1d Correlation matrix for 3rd Degree thickness residuals.

Vales Pt Coal Lens	1.00													
Karignan Congl. Mb.	0.01	1.00												
Wallarah Coal	0.17	0.02	1.00											
Mannering Pk C'lst.	0.24	0.01	0.10	1.00										
Toukley Coal Lens	0.05	0.05	-0.16	0.08	1.00									
Buff Pt. Coal Lens	0.04	-0.32	-0.20	-0.04	*0.50*	1.00								
Teralba Cong. Mb.	0.29	0.07	*-0.17*	*-0.33*	0.17	0.22	1.00							
C'lst. Roof	0.42	-0.35	-0.20	-0.08	-0.25	*-0.77*	-0.06	1.00						
Great Nthn Coal	0.23	*0.28*	*-0.24*	0.00	-0.25	-0.40	-0.05	0.11	1.00					
Eleebana Fm.	0.01	-0.07	*0.30*	-0.15	0.01	-0.22	-0.22	0.22	0.05	1.00				
Chain V'y Coal	0.00	-0.14	*0.26*	-0.15	-0.14	-0.17	-0.03	-0.02	-0.05	0.18	1.00			
C'lst Floor	0.16	0.11	*-0.23*	0.16	-0.03	*-0.56*	-0.08	0.03	0.03	-0.00	0.02	1.00		
Doyalson Fm.	0.03	0.11	-0.01	0.01	0.03	-0.08	-0.02	-0.45	-0.15	*-0.52*	0.18	-0.05	1.00	
(Sth) Fassifern Coal	0.06	-0.07	0.01	0.06	-0.06	0.35	-0.02	0.20	-0.05	0.04	-0.08	*0.23*	0.11	1.00

TABLE 6.2e Correlation matrix for 4th Degree thickness residuals.

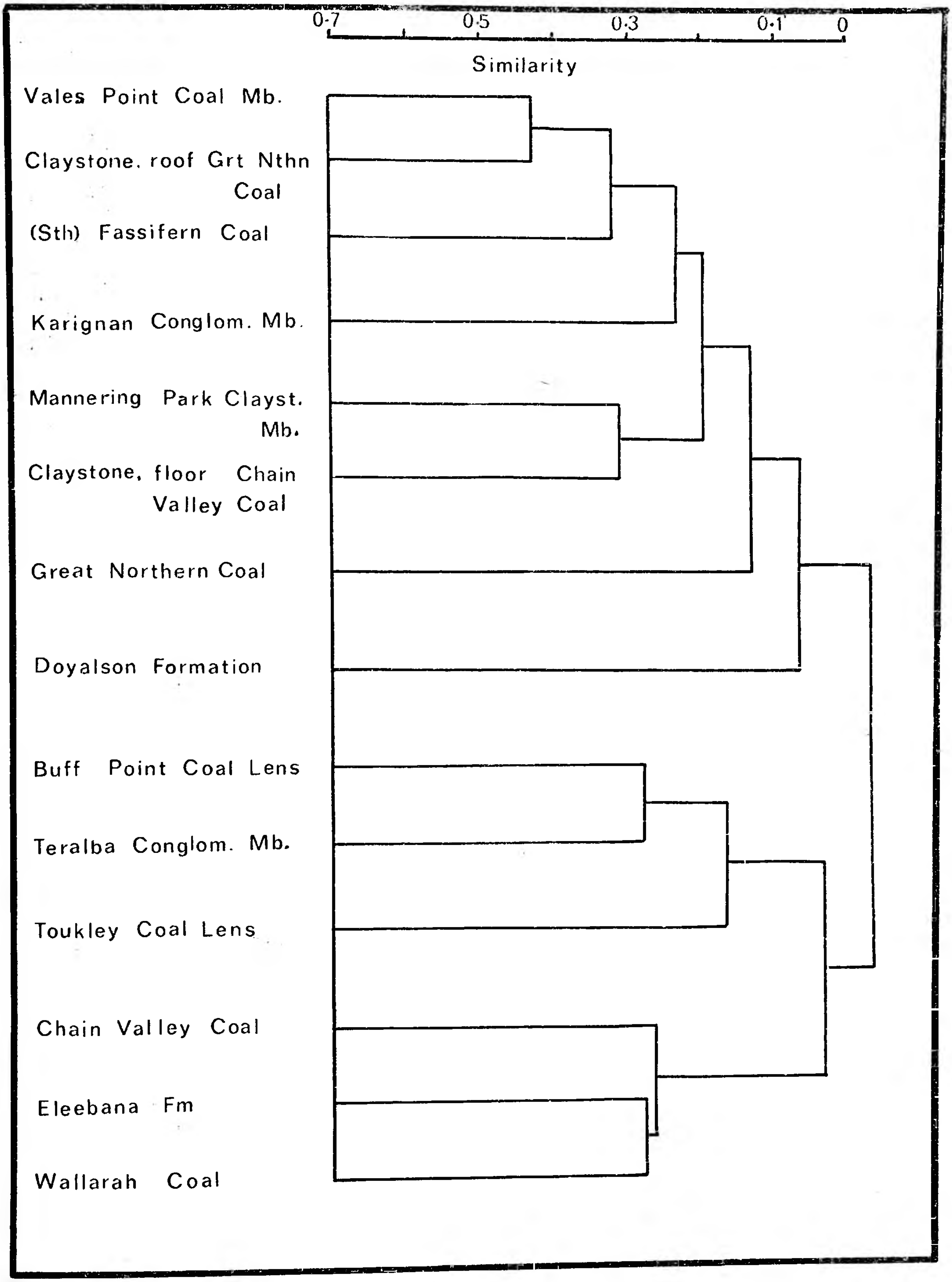


FIGURE 6.3a Dendrograph for raw thicknesses of units in the M.I.B.

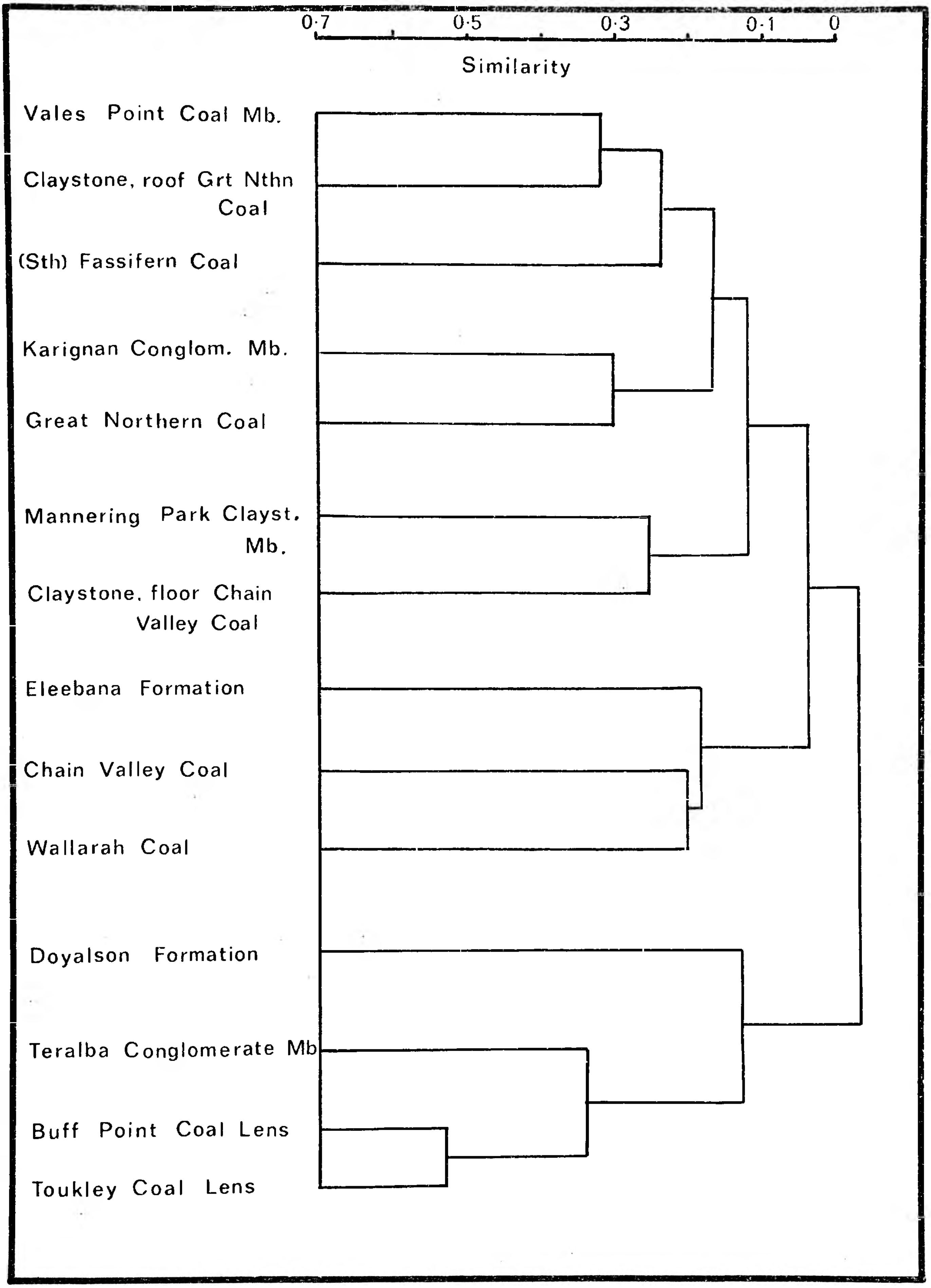


FIGURE 6.3b Dendrograph for the second degree residual thicknesses in the M.I.B.

inspection of residual and trend maps have no apparent causative relation to one another. Interestingly the Toukley Coal Lens and the Buff Point Coal Lens repeatedly clustered with the Teralba Conglomerate Mb. However, the residuals from the minor coal units are of dubious geological value while the clustering of these formations for the raw thicknesses is only barely significant.

The lack of marked groupings of the thickness data may be a result of the purely scalar approach of correlation methods in which the geographic distribution of the data is ignored. Thus relationships between certain units may exist only over part of the area and when the data for the whole areas are grouped the geographically-dependent relation becomes obliterated or less apparent.

Q-mode analysis methods may be successful in determining areas of similar behaviour but such analysis was not attempted here as there is an insufficient number of variables (formations) which extend over the entire map area.

While the clustering and association of formations in the cluster analysis was very weak it is interesting to note that the fine clastic units underlying the coal seams show only slight positive correlations with the overlying seam. Two such fine clastics, the Mannering Park Claystone Mb. and the claystone at the top of the Doyalson Formation and underlying the Chain Valley Coal are compared with their overlying coals. The Mannering Park Claystone Mb. yields only a weak, (+0.20, but significant at a 95% confidence level) positive correlation with the Wallarah Coal; the claystone at the top of the Doyalson Formation yielded a weak, non-significant positive correlation (0.09) with the overlying Chain Valley Coal. The low level of the correlation between the thickness of the fine clastics and the overlying coal seam could be taken to indicate the absence of any substantial relationship between the thickness of the fine clastic units and edaphic influences which in turn may affect the development of the peat on that sediment. The continued inorganic nutrition of the botanic community growing on thick (e.g. over 3m) peat must be derived from suspended clay fraction detritus brought into the swamp as overbank sediment rather than by extensive leaching and breakdown of the underlying sediment. The deposited sediment is preserved ultimately as included inorganic material or as discrete dirt bands.

Although the fine clastic sediment underlying the coals probably provided a supply of nutrients and formed a rooting bed for the first incipient, stabilising flora, the modification to the mineralogy and bedding in the sediment due to soil-forming processes is often only slight. Thus the macrotextures of seatearths of Carboniferous coals are not well developed and as a consequence a number of workers (e.g., Duff, 1967) have suggested a partly allochthonous or at least a non-autochthonous origin for the Sydney Basin coals. The existence of a positive correlation between the thicknesses Wallarah Coal and the Mannering Park Claystone Mb. is more a result for coincidental thickness development due to the persistence of tectonic subsidence patterns rather than any relation between the peat development and the thickness of the underlying fine clastic horizon (and the quantity of nutrients available therefrom).

6.3 QUANTITATIVE COMPARISON OF STRUCTURE AND THICKNESS RESIDUALS

It has already been established that the regional subsidence patterns which influenced clastic deposition and the accumulation of peat persisted through the M.I.B. and that the present-day regional structure is partly a manifestation of the original Permian differential subsidence. To determine whether the relation exists at a local scale several tests were performed using the raw and residual thickness data and the structure residuals.

6.3.1 Linear Correlation

Simple linear regression analysis was carried out between the raw thickness and four residual thicknesses, and the four structure residuals. Each of the five thickness variables were compared with those structure residuals of equal or higher degree to the thickness variable according to the format of the correlation matrices in Table 6.3 Relationships between thickness residuals and structure residuals of lower degree to the thickness residuals were considered to be likely to be casual in that any Permian tectonic subsidence pattern, now reflected in the present-day structure, should be at least as complex as,or more complex than the original subsidence pattern. The early subsidence patterns may become intensified, masked or even obliterated under the influence of subsequent deformations; it is unlikely that simplification of the early "structure" will occur.

Only the correlation matrices of the formations which show significant regional thickness trends are given in Table 6.3; correlation coefficients in italics are significant at a 95% confidence level on the basis of a Student's t test. Scatter diagrams are presented for the regressions along the major diagonal of the correlation matrices. As the data were standardised prior to the linear regression analyses the scatter diagrams are plotted over a range of ± 3.0 standard deviations for both thickness (ordinate) and structure (abscissa).

As can be seen from Table 6.3 and Fig. 6.4 the Wallarah Coal shows a very strong inverse relation between thickness and structure residuals (r_{max} = - 0.48 having a Student's t=4.9) indicating that the coal is locally thicker in areas

CORRELATION MATRICES					MATCH MATRICES			
Wallarah Coal								
	Structure				Structure			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Raw Th	-.41	-.30	-.25	-.13	.62	.63	.62	.61
1st Th	-.48	-.36	-.30	-.15	.68	.69	.64	.57
2nd Th		-.39	-.32	-.16		.64	.69	.58
3rd Th			-.35	-.18			.72	.63
4th Th				-.22				.62
(101 d.f.)								
Mannering Park Claystone Mb.								
	Structure				Structure			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Raw Th	-.07	-.19	-.19	-.26	.52	.58	.57	.57
1st Th	-.09	-.20	-.19	-.28	.51	.61	.60	.62
2nd Th		-.21	-.20	-.28		.62	.63	.65
3rd Th			-.20	-.30			.62	.66
4th Th (96 d.f.)				-.30				.65
Teralba Conglomerate Mb.								
	Structure				Structure			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Raw Th	.25	-.01	.04	-.10	.42	.54	.48	.55
1st Th	.28	.05	.08	-.09	.35	.47	.51	.56
2nd Th		-.06	-.02	-.14		.56	.54	.59
3rd Th			-.02	-.16			.53	.56
4th Th (98 d.f.)				-.18				.53

TABLE 6.3

CORRELATION MATRICES — MATCH MATRICES

Great Northern Coal

	Correlation: Structure 1st	2nd	3rd	4th	Match: Structure 1st	2nd	3rd	4th
Raw Th	*-.31*	*-.23*	-.15	-.11	*.60*	.56	.54	.55
1st Th	*-.36*	*-.26*	*-.17*	-.12	*.71*	.65	*.64*	.55
2nd Th		*-.27*	*-.18*	-.13		.64	.57	.55
3rd Th			*-.21*	-.16			*.60*	.54
4th Th (99 d.f.)				*-.18*				.53

Eleebana Formation

	Correlation: Structure 1st	2nd	3rd	4th	Match: Structure 1st	2nd	3rd	4th
Raw Th	-.12	-.03	*-.20*	*-.31*	.52	.47	.49	.57
1st Th	-.13	-.03	*-.23*	*-.35*	.53	.50	.58	.58
2nd Th		-.03	*-.23*	*-.36*		.52	.59	.58
3rd Th			*-.25*	*-.39*			.56	.58
4th Th (101 d.f.)				*-.40*				.59

Claystone, floor Chain Valley Coal

	Correlation: Structure 1st	2nd	3rd	4th	Match: Structure 1st	2nd	3rd	4th
Raw Th	*-.23*	-.15	-.11	-.02	.54	.59	.58	.57
1st Th	*-.24*	-.16	-.11	-.02	*.63*	.61	.57	.50
2nd Th		-.16	-.12	-.02		.59	.55	.57
3rd Th			-.13	-.03			.54	.53
4th Th (75 d.f.)				-.03				.53

TABLE 6.3 (cont)

	CORRELATION MATRICES				MATCH MATRICES			
	Doyalson Formation							
	Structure				Structure			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Raw Th	-.15	*-.21*	*-.30*	-.19	.55	.53	*.64*	.55
1st Th	-.18	*-.25*	*-.35*	*-.22*	.47	.51	*.64*	.60
2nd Th		*-.28*	*-.39*	*-.24*		.48	*.63*	.59
3rd Th			*-.39*	*-.24*			.59	.57
4th Th (74 d.f.)				*-.27*				.58
	South Fassifern Coal and Fassifern Coal							
	Structure				Structure			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Raw Th	*-.17*	-.01	-.07	-.10	.52	.48	.53	.55
1st Th	*-.17*	-.01	-.07	-.10	.55	.51	.57	.57
2nd Th		-.01	-.07	-.11		.51	.57	.59
3rd Th			-.07	-.11			*.61*	*.63*
4th Th (99 d.f.)				-.12				*.60*

TABLE 6.3 Matrices of correlation and match coefficients of structure versus thickness residuals and thickness raw data. (Correlation values in italics are significant at a 95% confidence level on a Student's t-test).

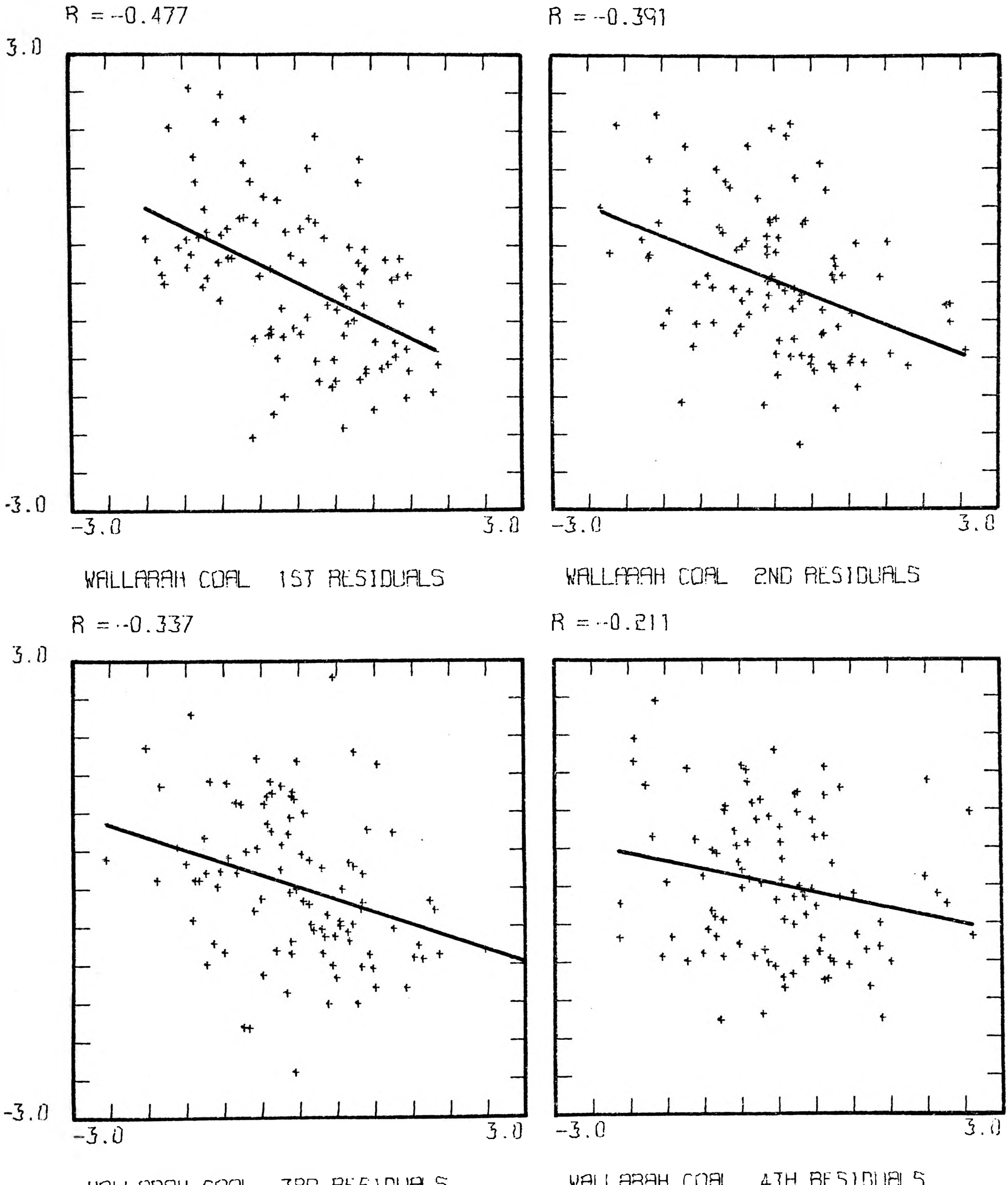


FIGURE 6.4 Linear regression correlation plots for major diagonal variables of the Wallarah Coal in Table 6.3

below the present-day regional structure and *vice versa*. The underlying Mannering Park Claystone Mb. also shows a statistically significant inverse relation between thickness and structure residuals. However the first degree structure residuals fail to significantly correlate with the raw thickness or the first degree thickness residuals (Fig. 6.5).

The Teralba Conglomerate Mb. (Fig. 6.6) except for the correlations with the first degree structure residuals generally does not indicate any significant relations between the structure and thickness residual data. The first degree structure residuals show a statistically significant positive relationship with the raw and first degree residual thicknesses. This direct relationship was inferred from the thickness residual maps in Chapter 5 and as mentioned above it may be partly related to subsequent differential compaction of the included lenticular coal lenses. Thus the positive correlation coefficients may not be indicative of any original causative relation. Further, the anomalous, inconsistent nature of the structure-thickness correlation matrix tends to cast doubt on the reliability of using data of the present-day compacted thickness of the Teralba Conglomerate Mb. to evaluate whether its deposition was controlled or influenced by a persistent basement subsidence pattern.

Linear regression analysis of the thickness and structure residuals of the Great Northern Coal (Fig. 6.7) reveals a statistically significant inverse relation between the two

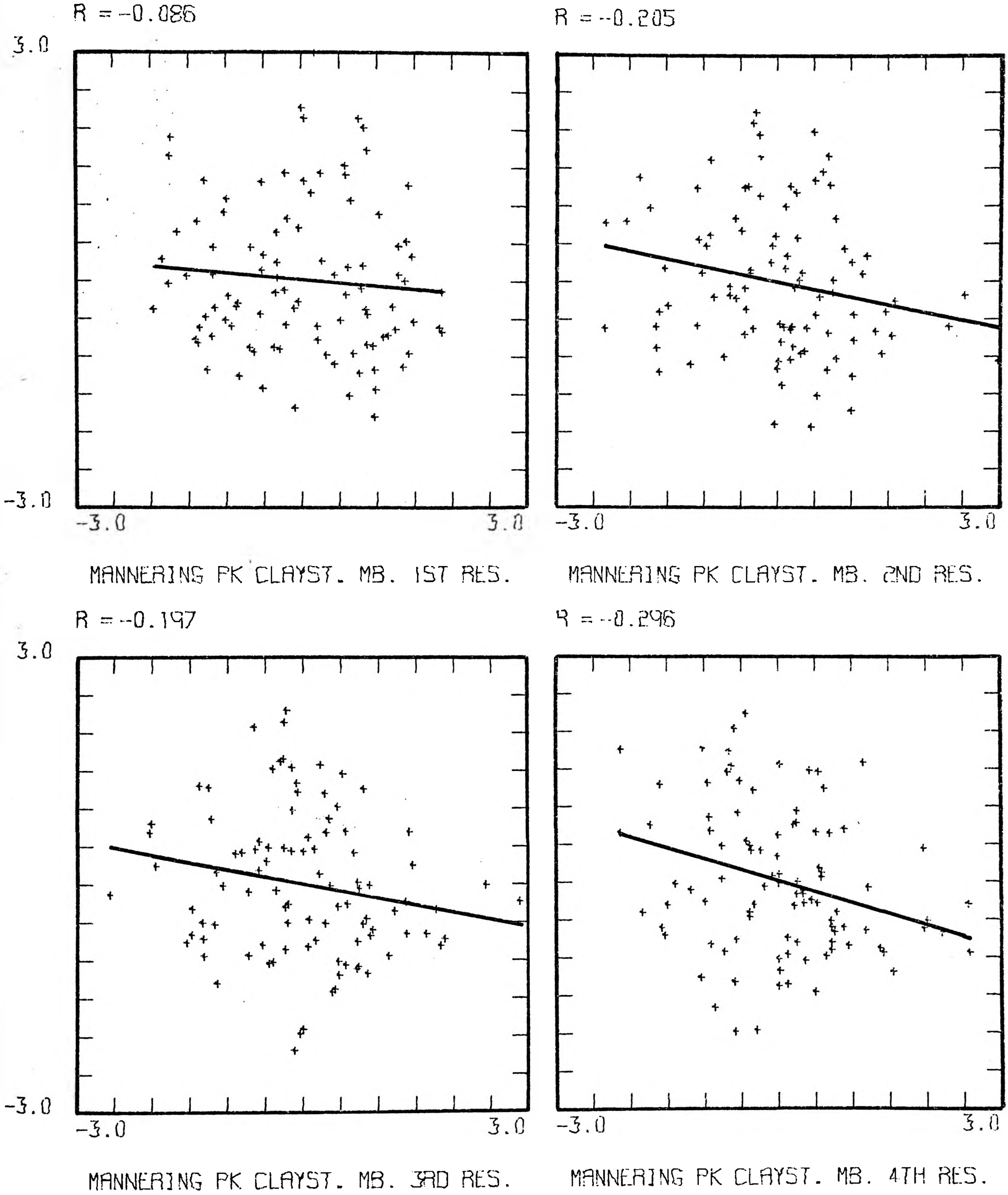


FIGURE 6.5 Linear regression correlation plots for major diagonal variables of the Mannering Park Claystone Mb.

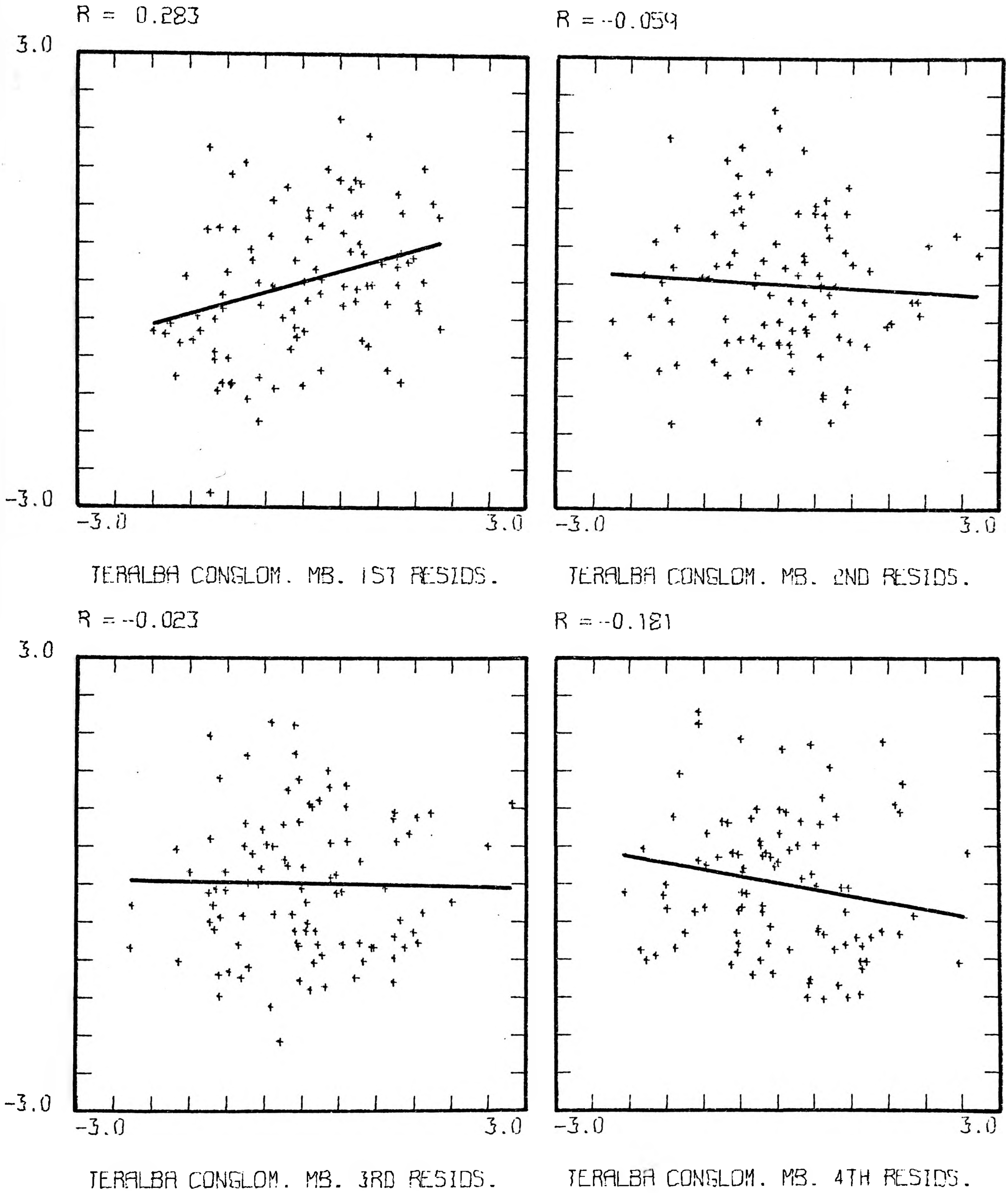


FIGURE 6.6 Linear regression correlation plots for major diagonal variables of the Teralba Conglomerate Mb.

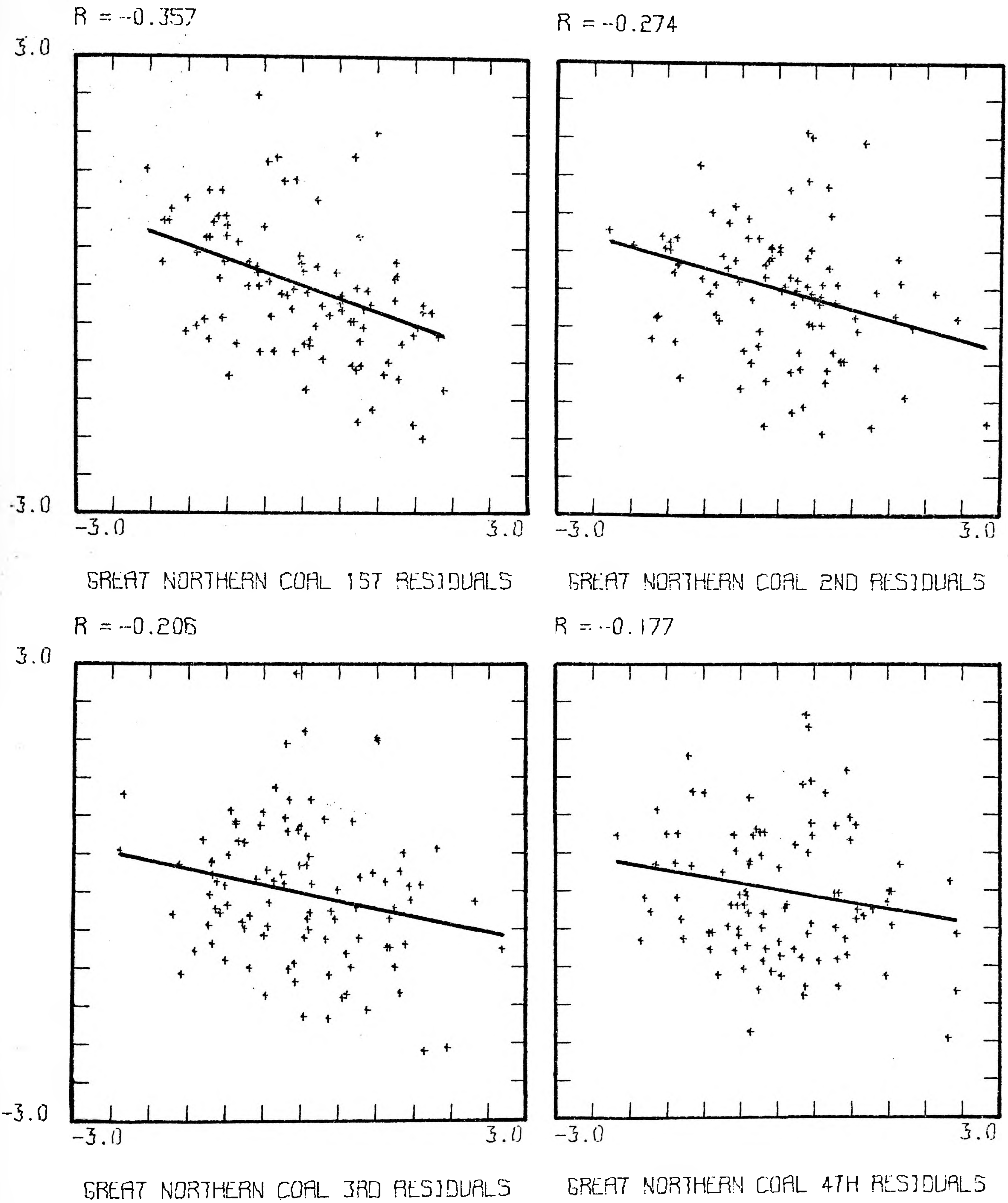


FIGURE 6.7 Linear regression correlation plots for major diagonal variables of the Great Northern Coal.

variables. Although the correlations are not as strong as those obtained for the Wallarah Coal the pattern of variation of the correlation coefficients in the matrices of the two coal formations is very similar. In both cases the coefficients increase towards the major diagonal and decrease along the diagonal, the maximum being for the first degree thickness residuals versus the first degree structure residuals. This pattern suggests that the variation associated with inverse relation between the residuals is partly accounted for by the degrees of freedom associated with the increasing degree of trend-surface, and hence there is no sharp boundary between the structure-thickness relationship at a regional and local scale.

The correlation coefficients for the Eleebana Formation (Table 6.3 and Fig. 6.8) are only statistically significant for regressions between the third and fourth degree structure residuals and the thickness variables; the relation is inverse. The absence of any relation for the low degree thickness residuals and the low degree structure residuals may be the result of the lithofacies variation within the Eleebana Formation and the rapid and localised thickness variations resulting from differential compaction of the various lithologies.

The claystone that underlies the Chain Valley Coal and forms the top of the Doyalson Formation shows only a weak

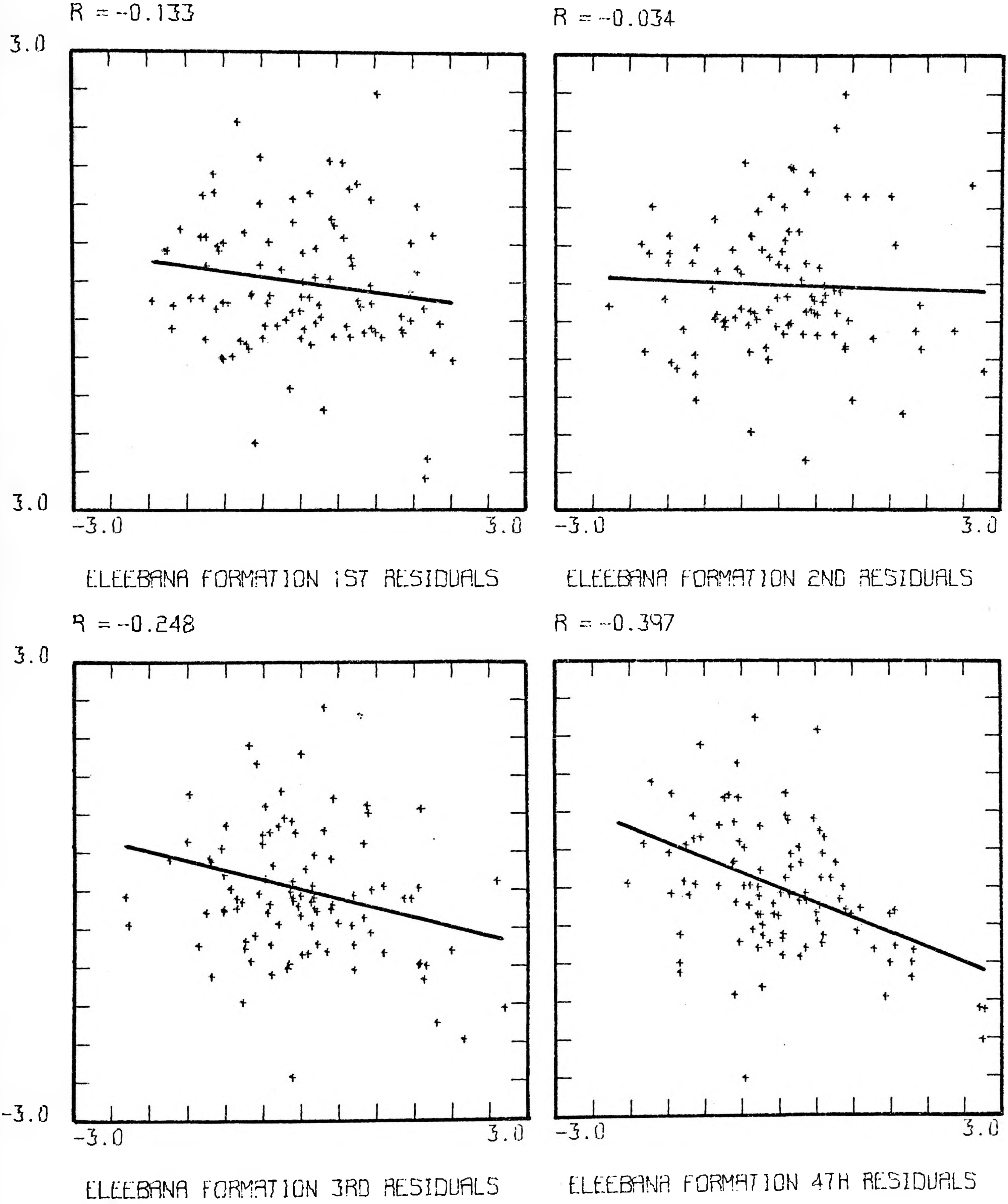


FIGURE 6.8 Linear regression correlation plots for major diagonal variables of the Eleebana Formation

(though statistically significant) relation between the first degree structure residuals and the raw thickness and the first degree thickness residuals. Other regressions are not significant at a 95% confidence level.

When the total thickness of the Doyalson Formation is analysed the regressions between the thickness and structure residuals all reveal statistically significant inverse correlations (Fig. 6.9), the only exception being the regressions with the first degree structure residuals. These results indicate that at a local scale the thickness of the Doyalson Formation is inversely related to the present-day structure residuals.

The Fassifern Coal and the South Fassifern Coal thickness and structure residuals when analysed for relations between these variables yielded weak, but statistically significant relations (Fig. 6.10), between the first degree structure residuals and the raw thickness and the first degree structure residuals. These results may partly be a reflection of the relatively high variance in the thickness data for the (South) Fassifern Coal caused both by difficulties in defining a consistent base level for the seam in many bores and by variations caused by local increases in the proportion of fine inorganic clastics in the seam.

Generally the results of the linear correlation between the structure and thickness residuals indicate an inverse relation between the present-day local structures and the raw

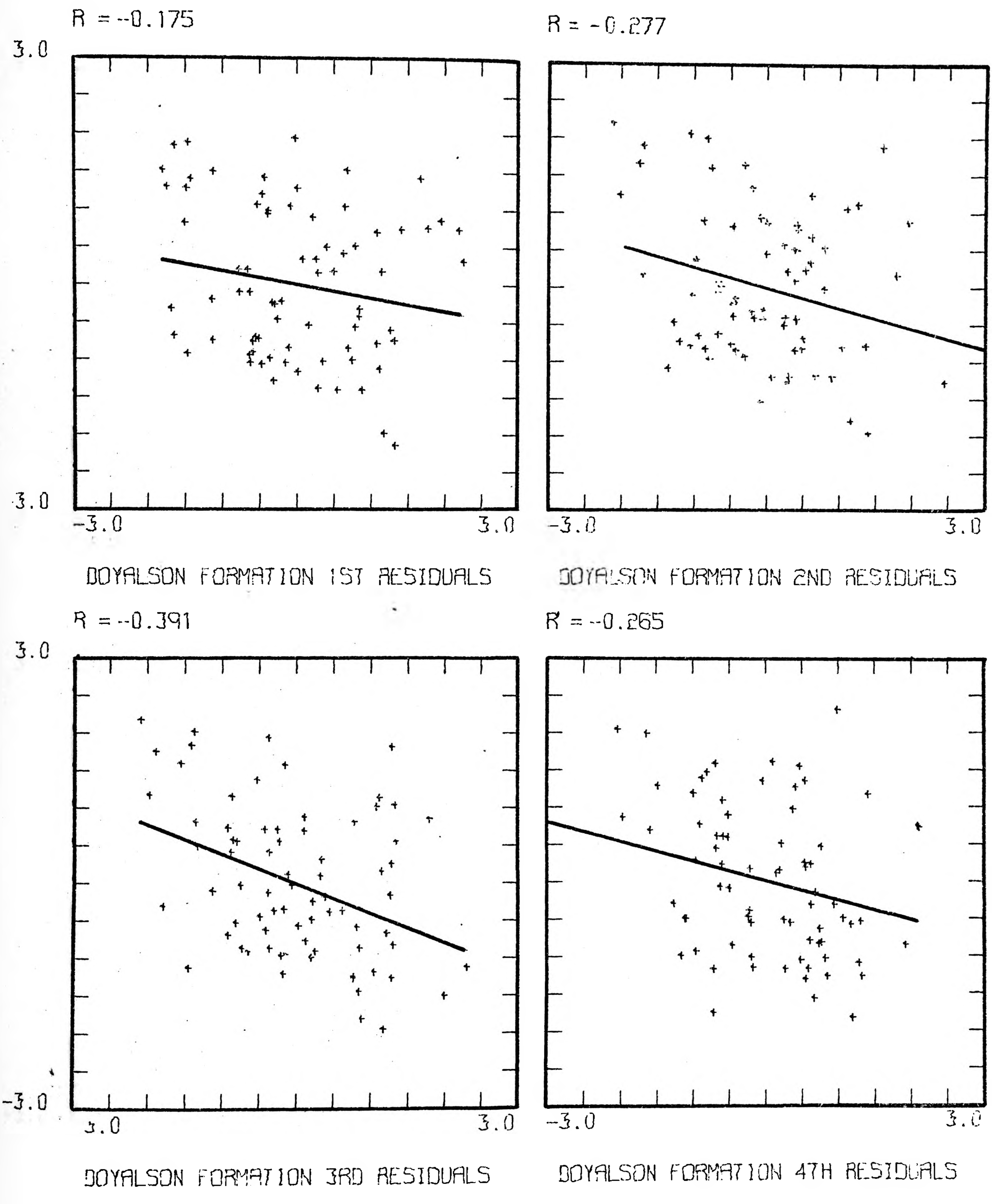


FIGURE 6.9 Linear regression correlation plots for major diagonal variables of the Doyalson Formation

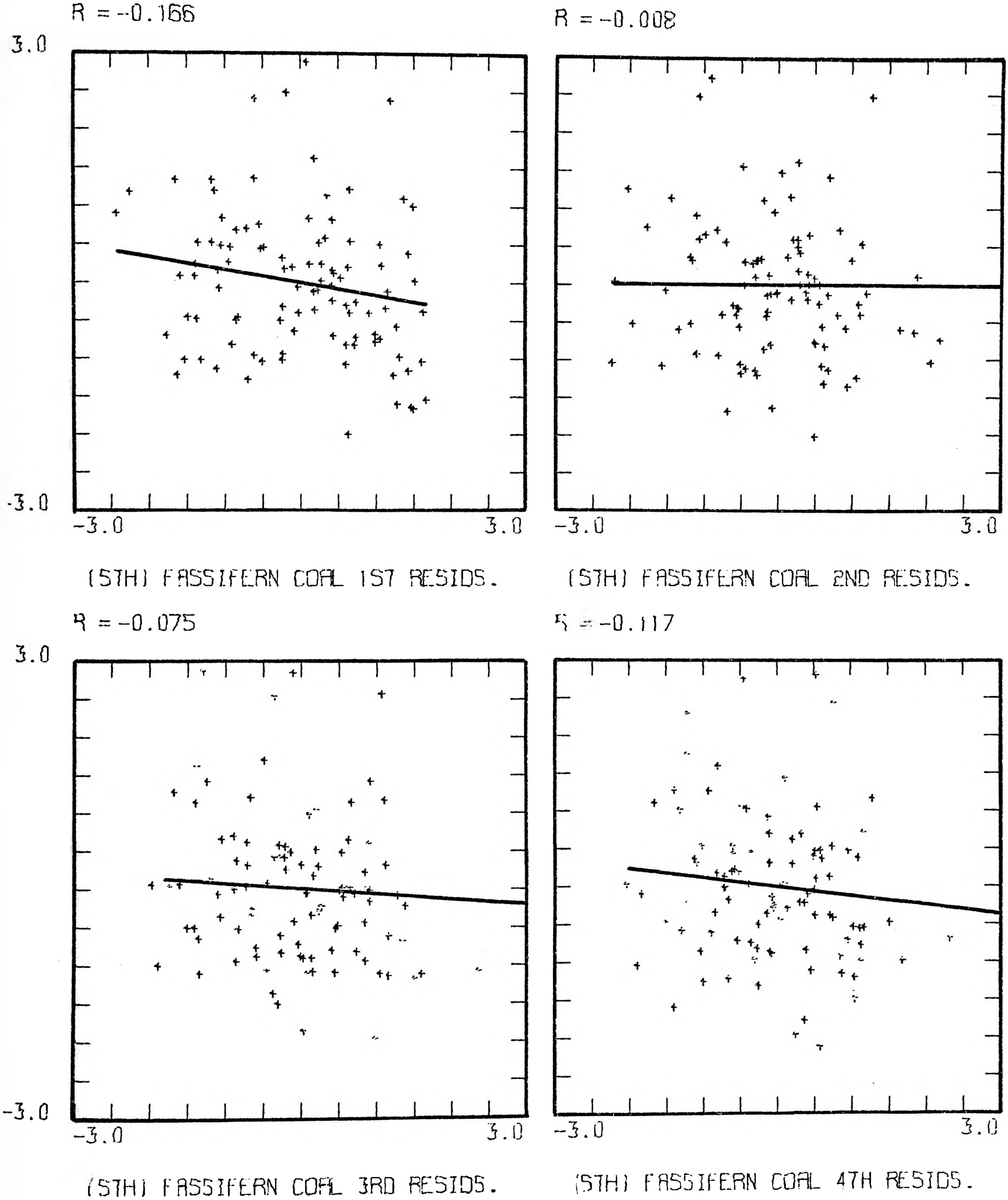


FIGURE 6.10 Linear regression correlation plots for major diagonal variables of the (South) Fassifern Coal

and residual thicknesses of a number of formations in the M.I.B. The relationship is strongest in the case of the Wallarah Coal and the Great Northern Coal. A possible explanation of the coals being most affected by local Permian tectonic subsidence patterns may lie in the time over which particular formations accumulated and the actual rate and frequency of the subsidence movements. Assuming a compaction ratio about 12 for coal, the uncompacted thickness of the Wallarah Coal for example, may have been in excess of 50m (of peat). The time required for the accumulation and preservation of this quantity of peat (given that a proportion is oxidised and not preserved) would probably have been very much greater than the time taken to deposit a clastic unit such as the Eleebana Formation. If tectonic subsidence, as opposed to compactional 'foundation' subsidence, was only at very slow rate then the more slowly accumulating units would be most influenced by basement subsidence patterns. Compactional subsidence may be of more consequence to the medium and coarse clastic formations which would probably have local variations in bulk density thereby causing local increases in compaction and relative subsidence. During the periods of clastic deposition, the rate of sediment influx probably exceeded the rate of tectonic subsidence, with compaction of the substrata of uncompacted, incompetent peat accommodating the sediment influx. Differential compactional subsidence during peat growth and accumulation would be less important in determining local thickness variations as no large, lateral density contrasts would be present within a body of peat.

There is a common tendency in most of the correlation matrices for the correlation coefficients to approach a maximum in the major diagonal of the matrices, the values increasing down each column but decreasing across each row. Hence first degree thickness residuals inversely correlate best with first degree structure residuals and so on. This behaviour would suggest that local Permian subsidence patterns have to a large extent been preserved in the present-day structure which can be regarded as an intensification of not only certain regional subsidence features (the synclinal component of the Macquarie Syncline) but also pre-existing local features in the tectonic subsidence. Localised subsequent deformations extraneous to the early subsidence do not appear to have significantly affected or masked the contemporaneous local structures.

6.3.2 Match Matrices

Match matrices were calculated for all the M.I.B. units studied and were derived by the method given by Section 3.5.3; the matrices for the units having significant regional thickness components are given in Table 6.3 along with the correlation matrices. The same variables were compared and the lower half of the matrices were not calculated for the reasons outlined above. The element in the match matrices is the fraction (decimalised) of data points which are either:

(a) Structure residual positive-thickness residual negative or,

(b) Structure residual negative-thickness residual positive.

The compliment of the numbers given are the fractions of bores whose residuals report to the opposite of the above. Hence the larger the number in the match matrix the stronger the inverse relationship between the structure and the thickness residuals.

The results of the match matrices closely parallel those relationships indicated by the correlation coefficients. Formations which indicated statistically significant inverse relationships between residuals yielded match coefficients of the order of 0.6 while those pairs which had no statistically significant linear correlation gave match values close to 0.5.

In Section 3.5.3 it was noted that a chi-squared test could be performed on match matrix data to determine the statistical significance of the degree of weighting in the matrix. Due to the limited type of classification afforded by the match matrix the degree of freedom is only one. Using this criterion the values in all match matrices are not significant at normal confidence levels. However, as the match values closely correspond with the correlation coefficients for the same variables, the chi-squared test in this instance is suspect. As there are no contradictions between the match coefficients and the correlation coefficients it would seem that the significance level based on chi-squared test is not appropriate.

An alternative test for determining whether the bias in the matching coefficients is significant is to carry out a test assuming that a random match coefficient is 0.50 and is described by the binomial distribution with the 95% confidence level equivalent to two standard deviations from the random level. The results of this test were more consistent with those for the correlation coefficients which were based on a Student's t-test. The match coefficients in italics in Fig. 6.3 are significant at a 95% confidence level using the binomial test.

The match coefficients only confirm and reinforce the results obtained in the previous section and are therefore not discussed further.

6.3.3 Match Maps

Match maps have been constructed according to the method outlined in Section 3.5.4; the match maps aim to define areas where the inverse structure-thickness relationship occurs and areas where there is a direct relation between the structure and thickness residuals. As the results of the linear correlation generally reveal either a statistically significant inverse relation or the absence of any relationship, only those units which have high inverse relationships between their structure and thickness residuals are considered here. Thus the Wallarah Coal and the Great Northern Coal match maps for the first three elements in the major diagonal are given in Fig. 6.11a,b,c and Fig. 6.12a,b,c. The first degree structure-first degree thickness residuals match map for the Fassifern Coal and South Fassifern Coal, being that pair of residuals which showed the highest inverse relation for that formation, is also given in Fig. 6.13.

The maximum possible range of values on the match maps is ±2.0. Values close to +2.0 or -2.0 indicate areas where the direct relation between structure residuals and thickness residuals exists, e.g. values close to -2.0 suggest very thin coal (negative residual) occurring in an area of extreme negative structure residual. In areas where the inverse relation prevails, the signs of the residuals tend to cancel each other and hence have values close to zero. In order to emphasise the geographic extent of the inverse relationship between structure and thickness a contour band of ±0.4 has been shaded.

The Wallarah Coal residual match maps (Fig. 6.11a,b,c) show that over the majority of the area the match values lie within the the specified ±0.4 band width. The inverse relationship between the structure residuals and thickness residuals is geographically extensive and not the result of a few localised areas where the relation is strongly obeyed thus weighting the results of the linear regression. The areas outside the bandwidth are of restricted areal extent and in most cases can be related to local extrema in the residual data. For example the negative match area in the far southwest for the first residuals match map is the result of the very rapid thinning of Wallarah Coal in an area of negative structure residual. This thinning is attributable to the thinning and facies change in the underlying Teralba Conglomerate Mb. which may have locally influenced overlying peat accumulation in the Wyong Slope area. The positive feature outside the band width in the Swansea Rise area is attributable to the local increase in thickness of the Wallarah Coal as a result of coal development in the lower shaly part of the seam (*vide* Plates 2.8 and 2.9). Similarly other deviations can be explained by local autocorrelated extrema in the thickness residuals that have slightly biased the value of the match figure. However although there are areas where the relationship does not appear to be valid it should be noted that all match values lie within ± 1.0 indicating that the direct relationship between the residuals is not present (direct relationship would be suggested by match values

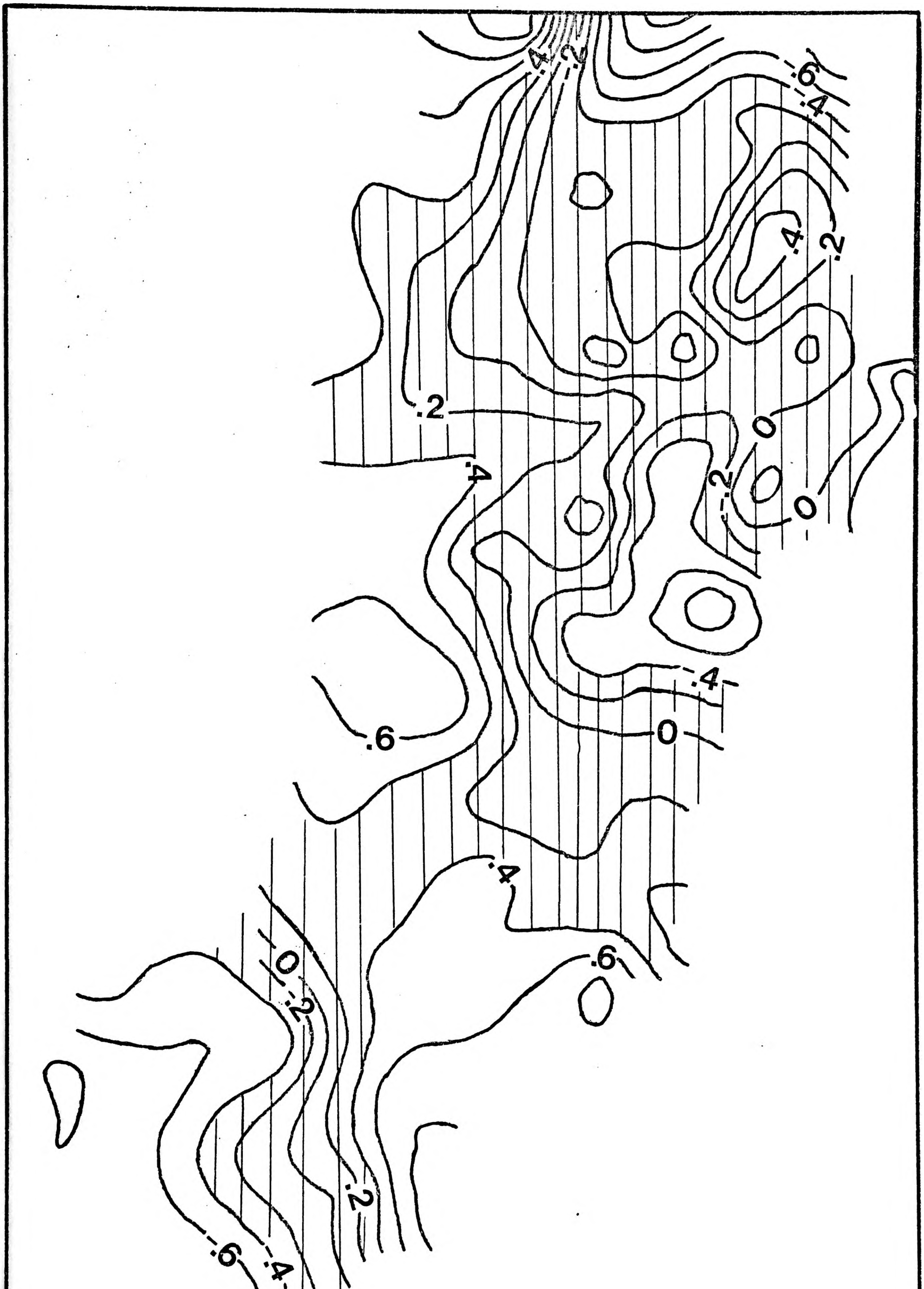


FIGURE 6.11a Wallarah Coal - 1st Residuals Match Map

Note: Hachured areas in this and subsequent match maps indicate match values in the range of +0.4 to -0.4. (Scale: 1cm = 1.5km)

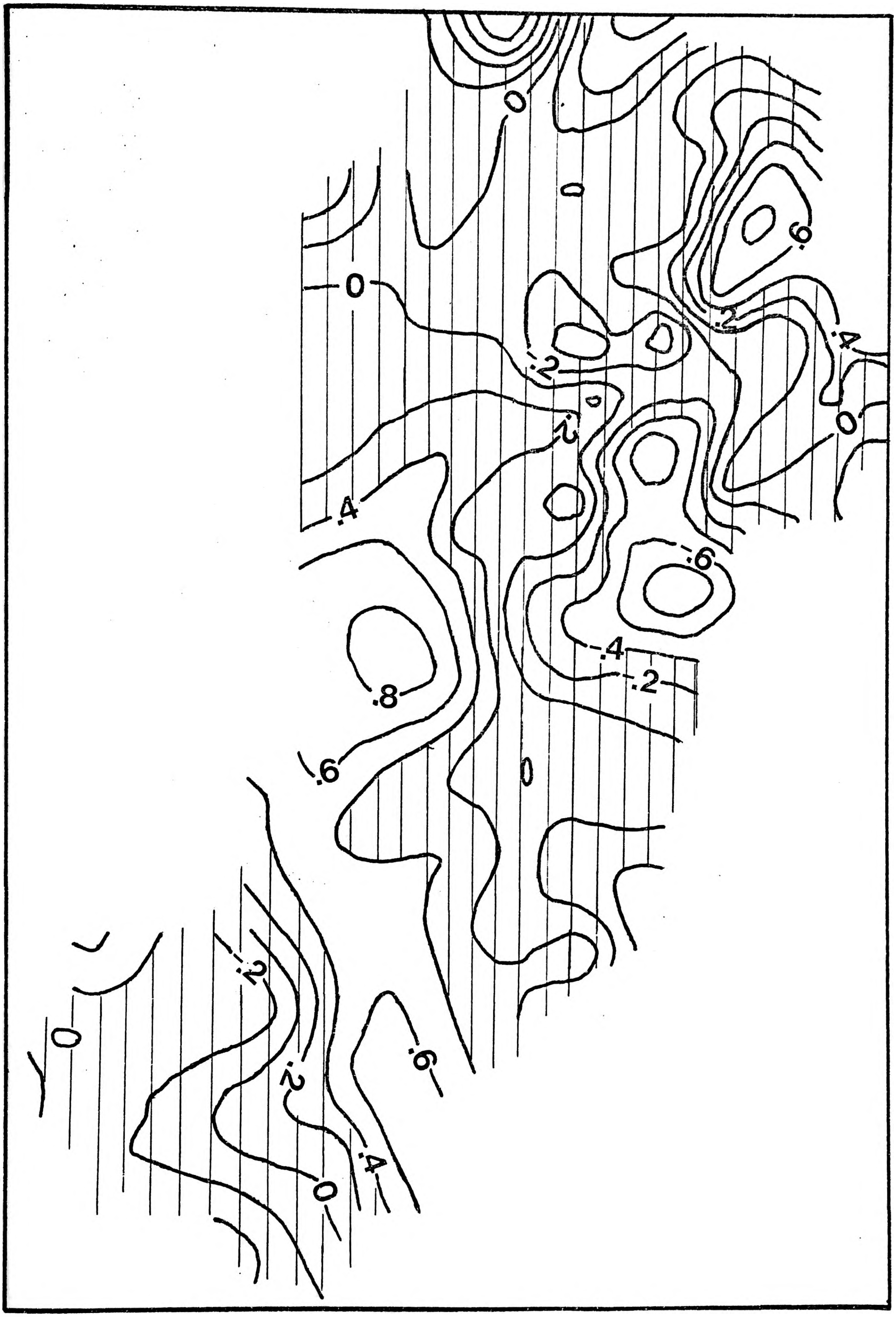


FIGURE 6.11b Wallarah Coal - 2nd Residuals Match Map

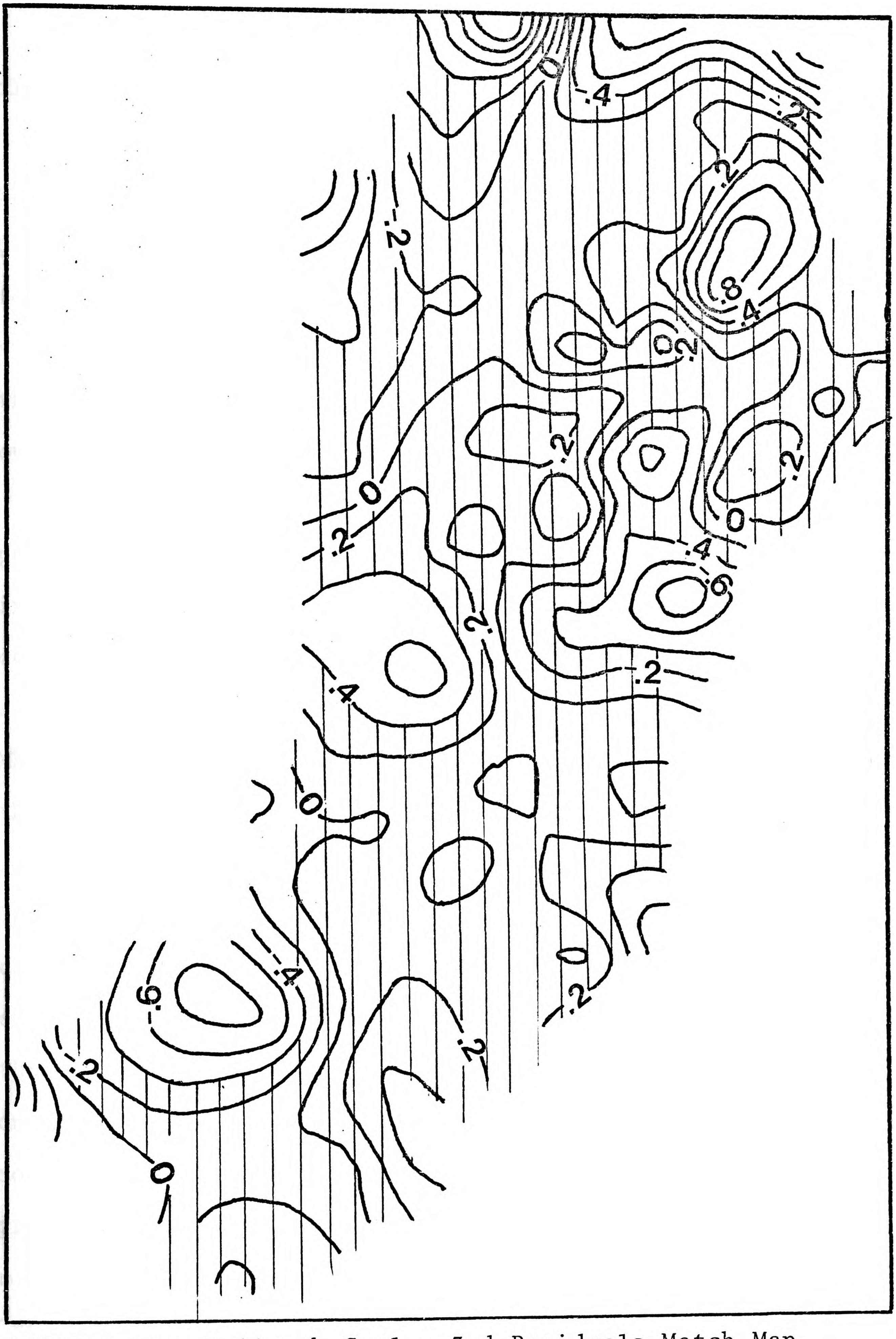
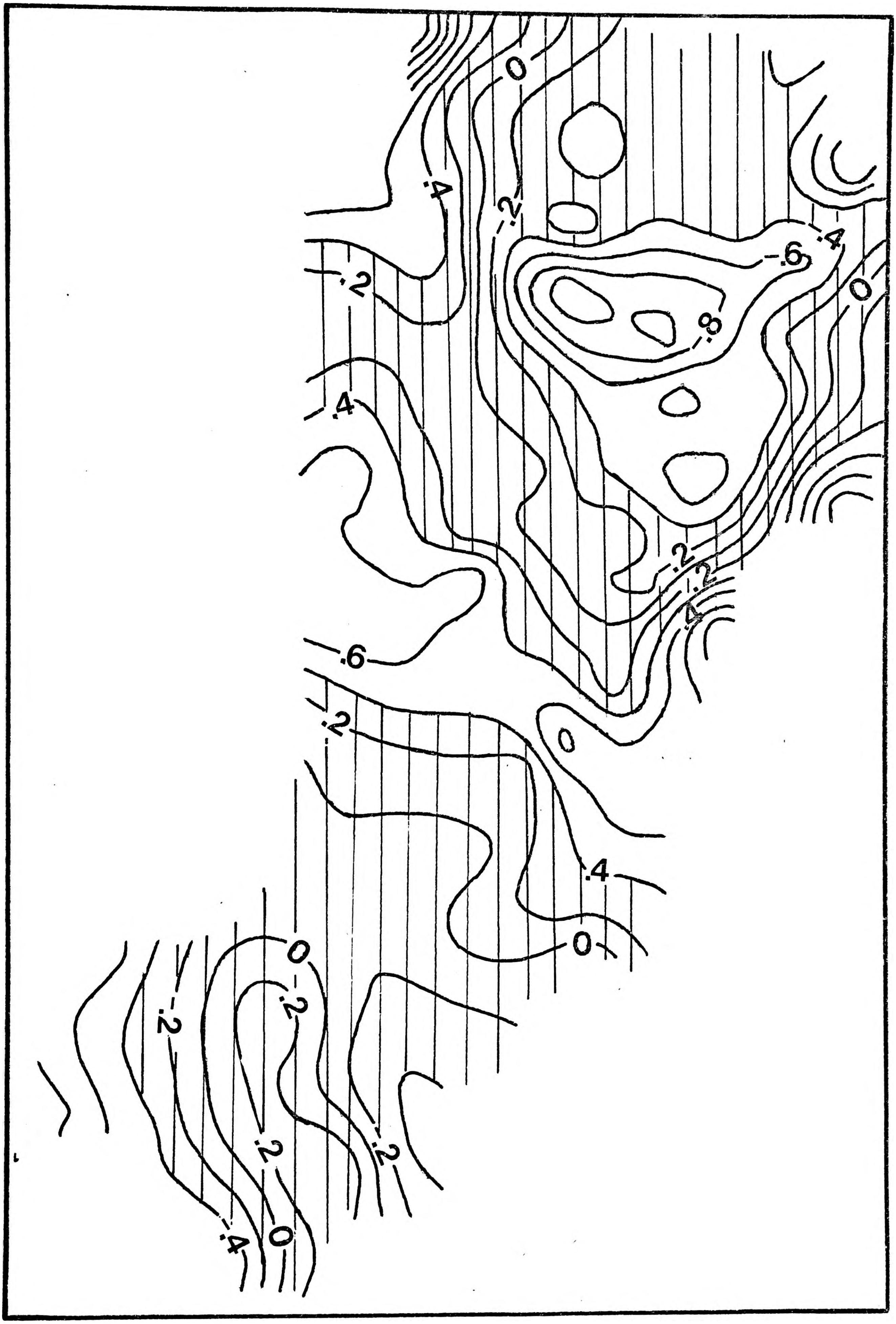


FIGURE 6.11c Wallarah Coal - 3rd Residuals Match Map

closer to ± 2.0).

The Great Northern Coal match maps (Fig. 6.12a,b,c) also show that the inverse relationship holds for a large proportion of the area studied. Similar to the match maps for the Wallarah Coal the Great Northern Coal maps are slightly weighted by the autocorrelation effects of the thickness residuals with the local deviations (i.e. areas outside the band width of ± 0.4).

In the north over the Chain Valley Depression there is a persistent negative match minimum. The Great Northern Coal in this area is very thin and in some bores is absent; the deterioration may be partly due to erosional influences associated with the deposition of the Teralba Conglomerate Mb. The combination of the negative thickness residual over the Chain Valley Depression (a strong negative structure residual) is sufficient to yield isolated match values as low as -1.0 but as with the Wallarah Coal apparent contradictions of the inverse structure-thickness relation are explicable in terms of local sedimentological controls rather than by the influence of direct structure-thickness controls on deposition. The areas outside the band width are slightly more extensive than the areas for the Wallarah Coal and this is probably a reflection of the results obtained in the linear regression (e.g., r = - 0.36 for 1st - 1st residuals of the Great Northern Coal as against r = - 0.48 for 1st - 1st



<u>FIGURE 6.12a</u> Great Northern Coal - 1st Residuals Match Map

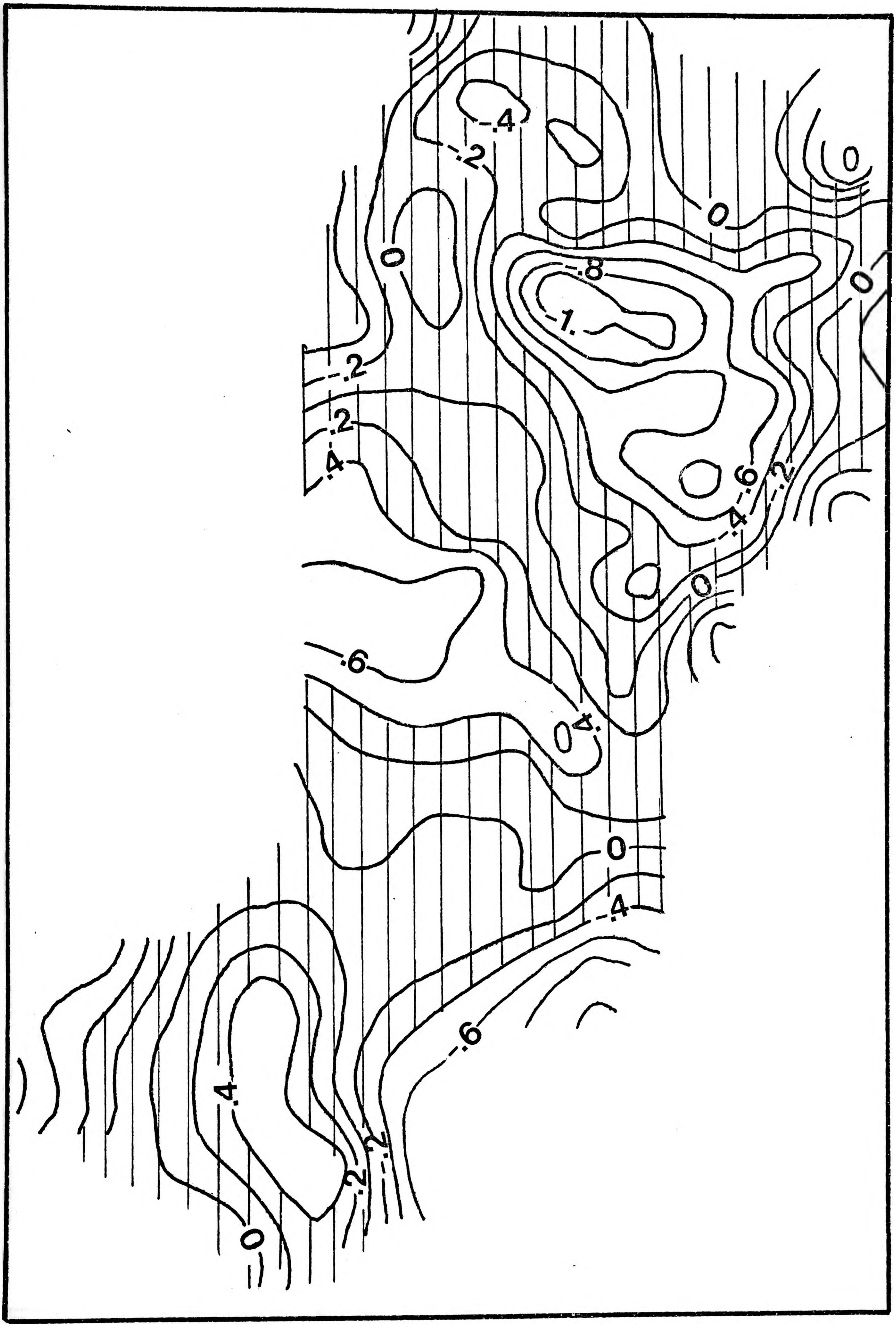


FIGURE 6.12b Great Northern Coal - 2nd Residuals Match Map

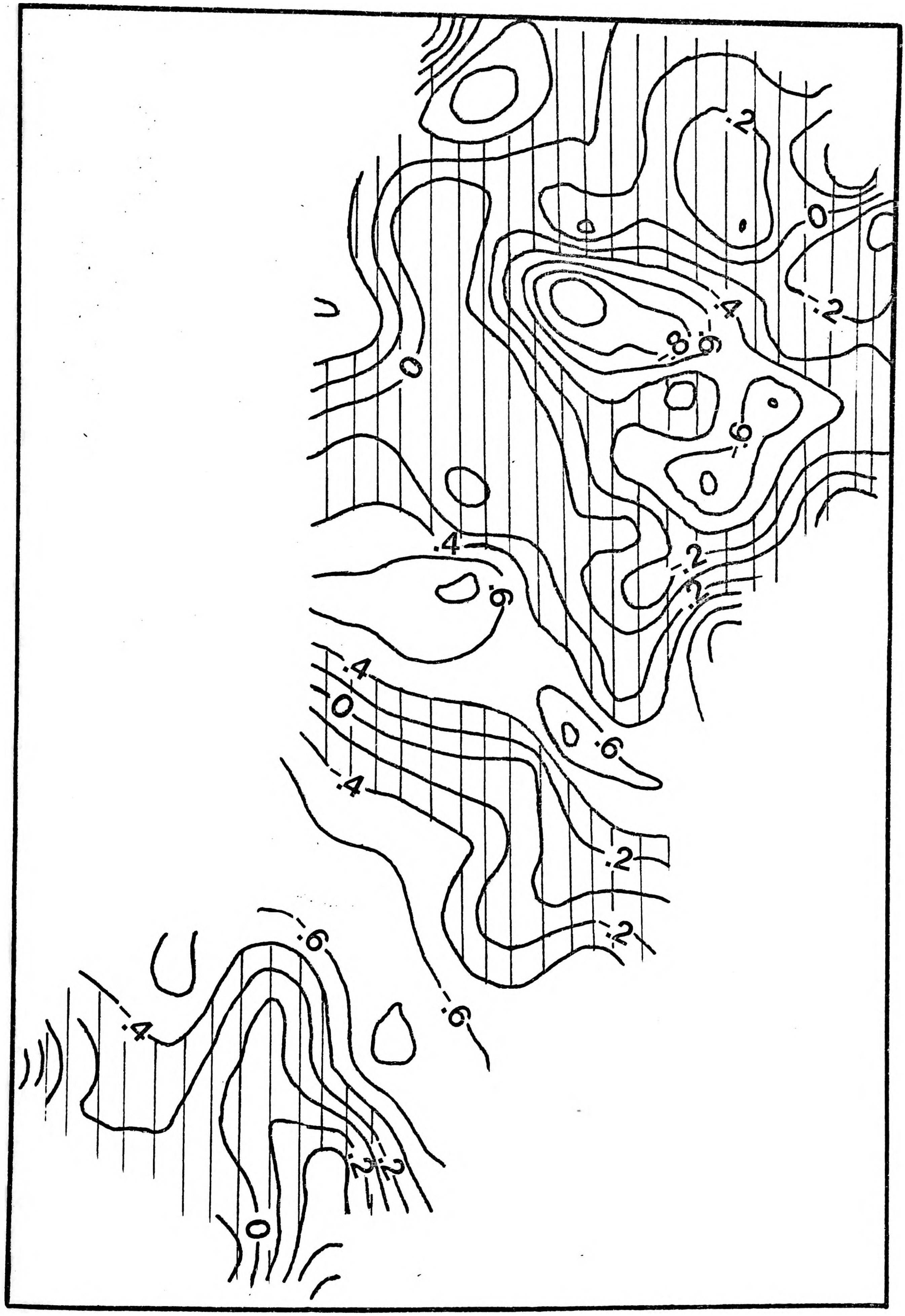


FIGURE 6.12c Great Northern Coal - 3rd Residuals Match Map

residuals of the Wallarah Coal.

The first degree residuals match map for the (South) Fassifern Coal is included for the purpose of comparison with the other coals which show stronger correlation coefficients. The (South) Fassifern Coal showed a low, but significant correlation coefficient (-0.17) and the match map reflects this low inverse correlation with a somewhat smaller area between the values of ±0.4 and also the existence extrema of the order of ±1.0.

The degree of persistence of the match areas and the mis-match areas through the M.I.B. has not been assessed quantitatively but, by inspection of the match maps there is a moderate degree of similarity between the (South) Fassifern Coal and the Great Northern Coal match configurations. There is also a general , but less marked similarity with the match domains for the Wallarah Coal. Persistent mis-match domains occur over the general areas of the Wyee Saddle, the Chain Valley Depression and the southern part of the Wyong Slope. Common match areas are around the margins of the Morisset Anticline, the Chain Valley Depression and the Wyee Saddle. The tendency for the minima and maxima of the structural domain to appear as mis-match areas in the match maps is probably the result of extreme thicknesses being recorded over these structures such that the match values fall outside

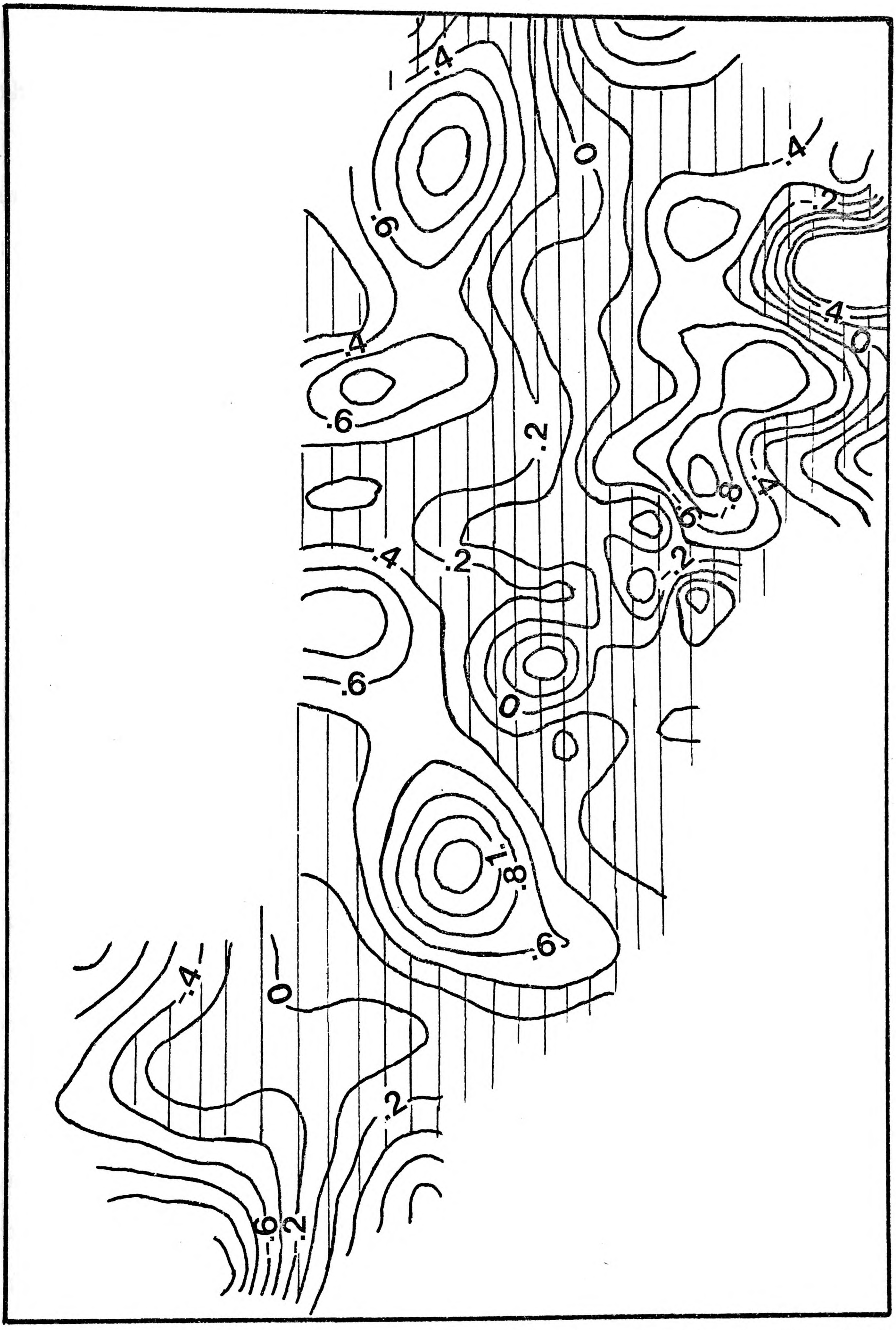


FIGURE 6.13 (South) Fassifern Coal - 1st Residuals Match Map

the ± 0.4 range.

In summary the results presented in this chapter unequivocally point to the existence of a differential, tectonic subsidence pattern which persisted both in loci and relativity throughout the deposition of the strata of the M.I.B. This subsidence pattern exerted a dominant control on the coal units but only marginally influenced the coarse clastic formations in their thickness development; the time over which the unit accumulated would seem to be an important factor in the degree of control and effect of this subsidence pattern on the development of the formation.

Not only has this Permian basement subsidence pattern persisted through the M.I.B. deposition but it has also been preserved in the present-day structure of the Sydney Basin as the synclinal component of the Macquarie Syncline. The present-day structure is the combination of subsequent uplift around the basin margins and an intensification of the Permian subsidence patterns along pre-existing basement failure patterns. Cook (1969b) suggested a block-faulting mechanism for at least the local basement subsidence patterns.

Compaction of immature peat would seem to be more of importance in determining thickness patterns of overlying coarse clastics. Tectonic subsidence does not appear to influence the thickness patterns of the coarse clastics to the same degree as those of the widespread coals. The compactability of clastic strata may also exert an influence on the accumulation of an overlying peat horizon and result in the formation of ephemeral subsidence patterns superimposed on the persistent background of the differential tectonic subsidence patterns.

CHAPTER 7

CYCLIC SEDIMENTATION IN THE M.I.B.: A DISCUSSION

7.1 INTRODUCTION

The results presented in the preceding chapters are oriented towards two main aspects of the depositional and structural history of the area. One relates to the generation of the sediment lithology sequence during the deposition of the M.I.B.; the other is concerned with the recognition of persistent and ephemeral Permian subsidence patterns and their relation to the present-day structure and thickness of lithological units.

Trend-surface analysis of the thickness variations of the successive units of the M.I.B. has demonstrated the existence of contemporary subsidence patterns during the accumulation of both the organic and inorganic phases. These subsidence patterns affected successive depositional events and partly determined the ultimate geometry and composition (in terms of grainsize) of the sediments. The initiation of stabilising vegetation, the pattern of the rate of accumulation of the peat and its ultimate cessation, are controlled regionally and locally by tectonic subsidence and depositional events. The internal dynamic controls on the successive depositional regimes have been demonstrated in a non-geographic sense by the results of the cycle and

Markov Chain analyses in Chapter 4. An evaluation and interpretation of the observed lithological variation in the M.I.B. and a comparison with other similar studies is presented here and inferences about the depositional environment of the M.I.B. are drawn.

7.2 COMPARISON OF RESULTS WITH SIMILAR STUDIES ON THE SYDNEY BASIN

The Markov Chain analysis showed unequivocally that the sedimentary sequence of the M.I.B. was not laid down in a random fashion and that the most probable sequence is a simple fining-upwards cycle terminating with an oscillating sequence of coal and fine clastics (claystone). Initiation of a new cycle is not part of the primary cycle path and only occurs as a secondary event.

The analysis of defined cycles in relation to other variables (thickness and mean cycle thickness) indicated that the number of cycles increased with increasing total thickness but that the mean cycle thickness decreased with increasing total thickness. Hence as the total thickness increases the development of additional cycles takes place rather than a simple linear thickening of the cycles parallel to the total thickness.

In understanding the geological significance of these results it is useful to compare other studies on both similar and different coal and non-coal bearing sequences.

However problems arise in the descriptive terminology used to classify the various cyclic sequences and, as mentioned in Section 4.1, nomenclature has been adapted to that discussed and adopted in Chapter 4.

Duff (1967) in a study on Permian cyclic sedimentation in the Sydney Basin, plotted the number of cycles ("exclusive of intraseam cycles") against the total thickness of sediment between marker horizons for a number of successions in the Newcastle Coalfield and the Southern Coalfield, N.S.W. He concluded that in the Southern Coalfield the number of cycles remains fairly constant but that in the Newcastle Coalfield the number of cycles increases with total thickness. Examination of Duff's (1967) data plots for the Newcastle Coalfield shows that the correlation coefficient for data from the interval between the Borehole Seam (base of Newcastle Coal Measure) and the Great Northern Coal is +0.33 which, being associated with only three degrees of freedom in the data is not significant at normal confidence levels. The correlation coefficient for the Borehole Seam to the Montrose Seam interval is much higher, and being associated with six degrees of freedom in the data, is statistically significant. It is, however, strongly dependent upon the outlying points and presumably contains the data for the larger interval, which are of doubtful significance.

Although data for the present study are from an area to the immediate south of that part of the Newcastle Coalfield studied by Duff and related exclusively to the upper part of the Newcastle Coal Measures, it is valid to compare the general relations detected in both studies. The essential character of the Newcastle Coal Measure does not change in this upper sub-group (M.I.B.) as compared with the lower sub-groups, the only apparent difference being an increase in the occurence of widespread conglomerate units. While this may increase the frequency of distinguishable fining-upwards cycles, due to the added lithology, the conglomerates appear only to increase the complexity of the fining-upwards cycles with conglomerate → shale (claystone) transitions rare or absent. Restricted lenses of conglomerate, common throughout the Newcastle Coal Measures, may cause seams to 'split' and in these cases an additional coal-cycle (and a fining cycle) will be developed.

While Duff's statistical analysis is not well controlled his conclusion that in the Newcastle Coal Measures the number of coal cycles increases with total thickness has been confirmed. This increase in the number of coal horizons with increased total thickness may be brought about by the following mechanisms:

(i) denudation by oxidation and erosion of peat horizons in areas of thin stratigraphic section (i.e. areas of low net subsidence and relative structure-high domains), or

(ii) development of areally restricted lenses of coal (e.g. Toukley Coal Lens) in Permian structure-low areas, or

(iii) the local interruption of peat development by deposition of substantial clastic wedges as channel-fill deposits in structure-low areas. The clastic wedge, whether it occurs in (Permian) structure-low or high areas will result in an increase in total section thickness. However the conglomerate wedges in the lower part of the Newcastle Coal Measures are confined to the axial region of the Macquarie Syncline (Branagan and Johnson, 1970). The only split seam in the M.I.B. (Fassifern Coal) also has its intervening wedge (Doyalson Formation) initiated and centred along this axial region.

For the M.I.B. thicker present-day sequences were also thicker Permian sequences (based on a high compaction ratio for peat) and, as has been demonstrated in Chapters 5 and 6, the loci and relativity of subsidence domains generally persisted throughout deposition of the sequence. Thus the inference is that thick sections correspond to areas of relatively greater Permian subsidence. The relation may even be stronger if the uncompacted Permian thickness is considered.

Each of these effects, causing additional coal cycles to be developed, are present in the M.I.B. and are evaluated below.

7.2.1 Contemporary Removal of Coal (Peat) Horizons

It is not uncommon for the Great Northern Coal, and to a lesser extent, the other widespread coal units of the M.I.B., to be locally absent or very much reduced in thickness especially if the usual overlying lithology is a conglomerate. For example the Great Northern Coal is absent in a few bores between Swansea and Morisset, and erosion of the peat by the overlying high energy alluvial detritus is probably responsible. The alternative hypothesis that peat (i.e. the Great Northern Coal) never developed in these areas seems unlikely in view of the widespread nature of the Great Northern Coal. These areas would have to have been entirely submerged at a depth unsuitable for vegetation or permanently exposed to extreme aerobic conditions where vegetable matter did not accumulate and peat did not form. In both cases a fining cycle would be expected at the probable Great Northern Coal horizon but in the bores where the Great Northern Coal is absent such remnants do not exist. Although denudation of the peat by oxidation probably did occur to some degree (*vide* Plate 2.4) which thereby greatly reduced the thickness, and perhaps the cohesive strength of the peat, this mechanism alone is inadequate in accounting for the absence of the coal. Both the fine clastic "seatearth" and the oxidised, (?) dehydrated peat were subsequently eroded by the streams depositing the conglomerate. The existence of erosional influences is also supported by observations in collieries and of outcrops where erosional relationships between coals and overlying conglomerates are evident (Plate 2.11). These comments also apply to the patchy occurence of the claystone which at times overlies the Great Northern Coal.

While the contemporary removal of peat is a mechanism which can account for the variation in the number of cycles developed over a given area it does not necessarily follow that the thickest section of sediment will occur where such erosion takes place. Hence the mechanism, especially given the probable rarity of complete erosion of fine clastics and peat, does probably not contribute significantly to the observed relationship between the number of cycles and the total thickness. Although most observations of total erosion of the Great Northern Coal occur in what were probable areas of low net subsidence the paucity of such bore intersections prevents the adoption of this mechanism as a major factor.

7.2.2 Restricted Coal Development

Within the M.I.B. apparently restricted coal development took place in at least three instances: the Tangy Dangy Coal Mb. (extreme south, Wyong Slope area), the Buff Point Coal Lens, and Toukley Coal Lens,(both confined to the central part of the area). The reasons for restricted lenticular development of a peat as opposed to the formation of the more usual widespread seams are not clear. These seams probably account for the observed positive relation between total thickness and the number of coal cycles and also the inverse relation between the mean cycle thickness and the number of cycles. A number of mechanisms can be postulated to explain the development of these seams particularly with regard to the upper two lenses. The southern geographic extent of the Tangy Dangy Coal Mb. is not known and although its development is probably restricted, it is partly conjectural to discuss its formation if its overall geometry is undefined. However the comments in this discussion with respect to the Buff Point Coal Lens and the Toukley Coal Lens are likely to be pertinent to the Tangy Dangy Coal Mb.

Trend-surface analysis of the Teralba Conglomerate Mb., which includes the two lenticular coal horizons, indicated a regional thickening along the Morisset Anticline, a probable zone of low net subsidence during the Permian. However the results of the trend analysis of the Teralba Conglomerate Mb. are to a certain extent suspect due to the differential compaction of the formation which may include up to two coal horizons. Hence the present-day thickness of the Teralba Conglomerate Mb. may be distorted as compared with the original thickness patterns when the uncompacted thicknessess of the coals are considered. Although the Teralba Conglomerate Mb. in the north and northwest of the area, where the Toukley Coal Lens and the Buff Point Coal Lens are absent, occupies a substantial proportion of the total thickness of the M.I.B., data from this area are not sufficient to weight the relation between the total thickness and the number of coal cycles. The coal lenses are best developed to the south of Lake Macquarie where the overall thickness of the section is greater due to the presence of the thick Doyalson Formation; the Teralba Conglomerate Mb. tends to be slightly thinner than to the north. However while this may account for the observed linear relationship between the number of cycles and the total thickness (an expression of total net subsidence) it still does not account for some bore sections around the southern end of Lake Macquarie. In this area some bores have a relatively thin Teralba Conglomerate Mb. section that includes one or both of these lenticular coals and adjacent bores where the lenses are not developed showing a thicker section of the Teralba Conglomerate Mb. In view of the importance of these minor coals in determining the observed cycle relationships the possible depositional and structural mechanisms which controlled the development of the areally restricted coal cycles and the role of subsequent compaction must be evaluated. Three hypotheses are outlined:

(a) The regionally thicker Teralba Conglomerate Mb. in areas of lower net subsidence may indicate that the channel loci for streams transporting the alluvial pebble sediment may have tended to be centred along the region referred to as the Morisset Anticline and the fine clastic horizons (the fining cycles below the lenticular coals) may be overbank phases of this deposition. Contemporaneous subsidence could have occured solely by compaction of the underlying peat horizons from the weight of the dense conglomeratic material. Channel loci may have been concentrated in this region by the relatively greater compaction due to the increased sediment load which initiated local depressions. Such a subsidence mechanism would in part be self-perpetuating until at least the difference in compaction of the underlying peat in the overbank areas and the peat below the channel zones became excessive and initiated meandering of the channels across the adjacent floodplain area with the consequent aggradation with the coarse sediment. In this model the Buff Point Coal Lens and the Toukley Coal Lens may be regarded as interdistributary peat "islands" phases developed on partly overbank areas.

(b) As noted above the Great Northern Coal is locally absent in some bores along this western high; aerobic denudation and erosion by streams depositing the conglomerate was the favoured cause. Similar influences may have removed peat and fine sediments associated with the Buff Point and the Toukley Coal Lenses from these areas. However although these coals are geographically limited in their extent they are continuous within their area of development. If these coals were erosional residuals a more haphazard distribution, such as that of the claystone that overlies the Great Northern Coal, might be expected. Further the general geographic coincidence of the Buff Point Coal Lens and the Toukley Coal Lens tends to negate this model in that it would require a delicate maintenance of the erosional patterns to remove large tracts of peat in the same areas at both horizons.

(c) A third hypothesis involves the activity of the persistent Permian basin structures to account for the distribution of the lenticular coals in the axial region of the Macquarie Syncline. Influx of the conglomerate prior to the development of the Buff Point Coal Lens may have taken place at a rate too rapid to reflect any structural control. An hiatus in the deposition of the conglomerate resulted in the development and preservation of a fining-upwards cycle. The fine clastics may either be an overbank phase or an outwash phase. During this depositional hiatus vegetation may have developed on the fine sediment. Gentle differential subsidence associated with the persistent basin structure may have occured along the axis of the Macquarie Syncline such that the vegetable matter was preserved and peat accumulated only in this region. In areas of lower net subsidence organic debris oxidised and peats did not form. The poor development and lack of continuity of the fine clastics in the areas of low net subsidence may be attributable to erosion by the next depositional phase of the Teralba Conglomerate Mb. or perhaps there was some structural control on the deposition of the fine clastic sediment. Peat accumulation may have been terminated by excessive subsidence or changes in the drainage pattern (or both) of the streams transporting sediment into the northeastern part of the Sydney Basin. A similar restricted peat development was initiated at the termination of the next conglomerate phase and the same subsidence patterns determined the geographic extent of the Toukley Coal Lens. In this model it is unlikely that channel loci were biased along particular structural regions as the rate of deposition would greatly exceed the rate of tectonic subsidence. Hence any relationship between present-day thickness patterns of the Teralba Conglomerate Mb. and the present-day structure may not be relatable to a direct structural control on deposition. The present-day thickness may represent a reversal of the original uncompacted thickness patterns due to the differential compaction of the various lithologies which may occur in the section. This latter model is the only model which is able, satisfactorily, to account for the compaction effects which must have operated during the deposition of the conglomerate as well as the coincidental geographic extent of the two coal formations. If a conservative compaction ratio between 5 and 10 (Elliott,

1969) is taken the thickness of the expanded sections of the Buff Point Coal Lens and the Toukley Coal Lens easily accounts for the observed differences in the present-day thickness of the Teralba Conglomerate Mb. This compaction effect also highlights the problems and dangers of analysing the thickness variations of units which contain a number of different lithologies. Indeed Blayden (1971) made this mistake when he attempted to establish if the Macquarie Syncline was manifested in the thicknesses of the Permian strata. He plotted the thicknesses of the four main sub-groups of the Newcastle Coal Measures and understandably dismissed the hypothesis that the Macquarie Syncline was a pre-existing Permian subsidence feature. Recent work by Wermund and Jenkins (1970) on the use of trend-surface analysis in identifying Pennsylvanian deltas in central Texas also confirms the necessity of confining separate analyses to individual facies.

Generally speaking Duff's (1967) conclusion that in the Newcastle Coal Measures the number of cycles increases with total thickness has been confirmed. The main contribution of the additional cycles comes from the development of lenticular coal horizons in areas of greater total thickness of the M.I.B. The inverse relation between the number of cycles and the mean cycle thickness is probably caused by the slow accumulation and the subsequent removal of peat horizons in areas of lower net subsidence and reflects the unfavourable conditions for the preservation of organic material which may have accumulated in these areas. In regard to this latter relationship the work of Read and Dean (1967, 1968) on the Namurian Coal Measures of Scotland provides a more useful comparison.

7.3 COMPARISON OF RESULTS WITH SIMILAR STUDIES ON OTHER BASINS

Read and Dean (1967, 1968) using variables similar to those analysed here showed that the thickness and cycle variables tended towards a linear relationship with each other and suggested that the variables were related to the total basin subsidence. Their six variables were grouped, with trend-surface analysis, into two contrasting sets, one characterised by wedge patterns associated with the mean position of a fluctuating shoreline, and the other by basin patterns associated with the total subsidence.

In the M.I.B. most of the variables appear to be related to net subsidence, accepting that the areas to the east and west (i.e. the anticlinal areas of the Morisset Anticline and the Swansea Rise) were subsiding at a slower rate than the central synclinal region. For the M.I.B. data the linear regressions of the average coal cycle thickness and the average fining cycle thickness versus the total thickness each yield positive correlation coefficients but in the case of the average coal cycle thickness this was not significant at normal confidence levels. On the other hand Read and Dean (1967) found a strong positive correlation (a basin pattern) for the mean thickness of complete (coal) cycles and total thickness. While the mean fining cycle thickness increases significantly with total thickness, the weakness, and perhaps absence, of a relation for mean coal cycle thickness as a function of the number of cycles would seem to reflect that vegetation horizons are not everywhere developed on each fining-upwards cycle. This effect is probably most marked in the areas peripheral to the synclinal zones where the restricted coals are not developed, but the section remains quite thick which results in an increase in the mean thickness of a cycle. In these areas, fining cycles, but not coal cycles (i.e. peat accumulation as the final stage of the fully developed cycle determined in the transition probability matrix of all bores in the Markov chain analysis) developed. Across the areas of lower net subsidence (thinner sections) the complete fining-upwards cycles themselves are not developed as the fine clastic unit is frequently absent (which consequently leads to difficulties in correlation). As is suggested by the Markov Chain analysis (Table 4.3) these sections have degenerated to oscillating coarse-medium clastic sequences and are not detected as fining-upwards cycles in either method of analysis. Consequently the nature of the mean coal cycle - total thickness relation is perhaps useful in understanding the lateral equivalents of the fine clastics and coals which are present in the areas of greater subsidence. In contrast to the relationships of average cycle thickness to total thickness, the correlation coefficients of the average cycle thickness with the number of cycles are negative and statistically significant for both fining and coal cycles. The reversal of the signs does not appear to be attributable to any perturbations caused by the data distribution or by the integer nature of the number of cycles variable. It is rendered possible by the relatively low values of the correlation coefficients involved (viz. the percentage of the variation explained does not exceed 43%). A similar reversal of signs can be found in the data of Read and Dean (1967) which has been included in Table 4.5 for comparison. The value of Read and Dean's correlation coefficient for the average cycle thickness as a function of the number of complete cycles (-0.15) is not significant at normal confidence levels but it is significantly different from the correlation coefficient for the average cycle thickness as a function of the total thickness (+0.63). The relatively strong negative correlations found for the M.I.B. average cycle thickness as a function of the number of cycles suggests a difference in the subsidence - sedimentation balance relationships as compared with the successions studied by Read and Dean (1967).

A number of other similar sedimentary sequences have been analysed using Markov Chains to determine ordering patterns in the lithologies. Apart from the work mentioned in Chapter 4, additional studies includes Doveton (1971) on a Carboniferous coal measure sequence in the United Kingdom and Selley (1970) on a number of non-coal bearing sequences. Although there are minor variations in the results of the different studies, especially those on (coal measure) sequences containing transgressive marine horizons, coal measure sequences invariably show strong non-random transition matrices which indicate a tendency for upwards-decreasing energy in the depositional environment (whether fluviatile or deltaic) with coal and peat as the terminal phase of depositional system. Also the Markov Chains strongly show that coal measure sequences are generally asymmetric cyclic sequences of the type outlined in Section 4.1.

Allen (1970) in a study of fining-upwards in fluviatile environments (especially in regard to Devonian sandstones in England) found results consistent with those observed in the Markov Chain analysis of the M.I.B. sequences. He found that each fining cycle consisted of a lower coarse member (lithologies of conglomerate or sandstone) preceding a fine member (lithologies of medium-fine sandstone and claystone) and concluded that "each cyclothem records the establishment of some kind of channel system and then its abandonment by the stream and burial beneath a floodplain". The cyclothems of the M.I.B. are simply an extension of the fluviatile fining-upwards cycle with the development of a vegetation stage which stabilised the floodplain sediment and accumulated upon it. The development of the peat stage is a reflection of both the overall paucity of sediment supply and the climatic-botanic conditions which prevailed. Hence for relatively short periods of time fluviatile deposition of coarse sediment in low-meandering streams took place in broad local areas (e.g. of the size of the Macquarie Syncline area) of the Sydney Basin. The deposition was perhaps initiated and terminated by major changes in drainage patterns outside these areas. Fining cycles developed and were preserved on the top of the coarse sediment upon the relaxation of the sediment supply; the fine sediment formed the substratum of the ensuing coal swamp.

When the environmental aspects of the results of the cycle analysis are considered in the light of the results of Read and Dean (1967) the M.I.B. cycle results imply that either the conditions for growth and accumulation of vegetation were more favourable in the areas of increased subsidence or coal horizons were present over the whole area and in the areas of low net subsidence were removed by oxidation or penecontemporaneous erosion or both. As outlined in the discussion of the origin of these restricted coal formations in Section 7.2, limited deposition of the peat

FIGURE 7.1 (a) and (b) Environments associated with deltaic deposition and possible interpretation of Moon Island Beach Sub-group cycles compared with cyclic sedimentation in the successions studied by Read and Dean, 1967, (Namurian) and Duff and Walton, 1962, (East Pennines).

(c) Interpretation of environment of deposition of coal lenses restricted to the axial part of the syncline.

(d) Simplified cross-section of the succession resulting from (c).

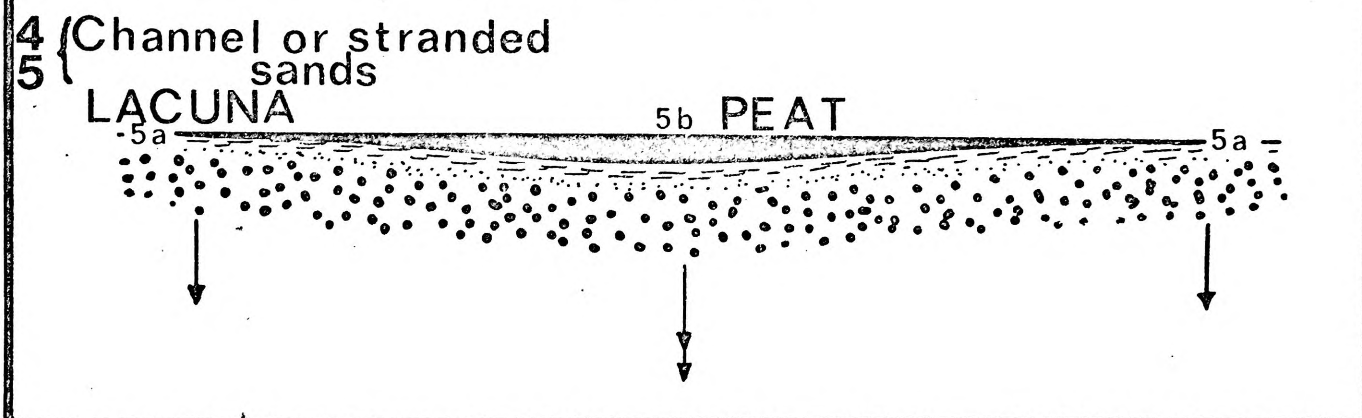
a ENVIRONMENT — CODE

ENVIRONMENT	CODE		
MARINE	1		
LOWER DELTAIC CHANNEL	2		≡ 4
LOWER DELTAIC OVERBANK	3	a. Dry	≡ 5a
		b. Wet	≡ 5b
UPPER DELTAIC CHANNEL	4		
UPPER DELTAIC OVERBANK	5	a. Dry	
		b. Wet	

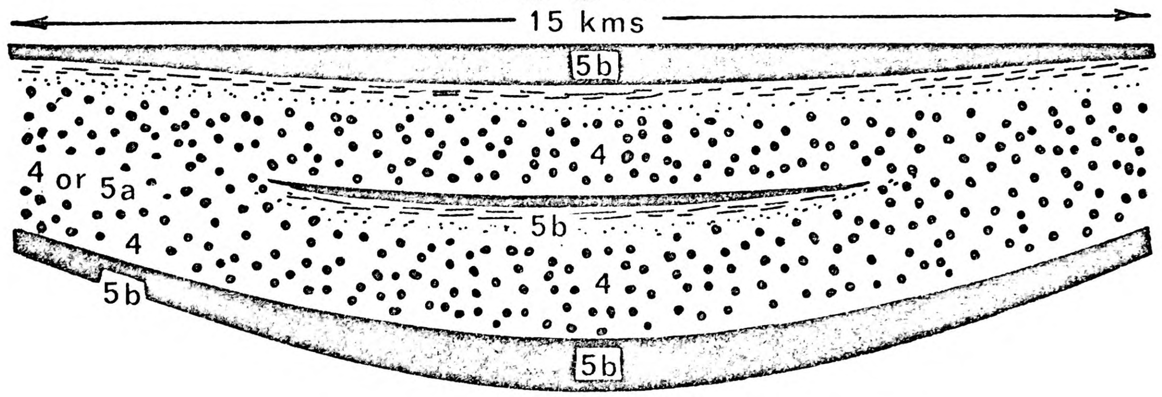
b CYCLES

Macq. Syncline			Scotland (Namurian)	East Pennines
	5b	5b		
	4	4	3	3a or b
5b	5a ≡	5b	2	2
4	4	4	1	1or 2

c PROCESS



d RESULT



and the fine clastics is the preferred explanation. This model is outlined diagramatically in Fig. 7.1 in which comparisons are also given between the probable sedimentary environments of the East Pennines of England and the Namurian Coal Measures of Scotland.

The gradient of the relationship between the average cycle thickness and the total thickness of the succession (or the total number of cycles) may be a sensitive environmental indicator. As total thickness is a reasonable net subsidence index, these relationships should be sensitive to the balance between sediment supply and subsidence and provide a measure of the degree of local as well as regional tectonic control on the areal sedimentation pattern and the accumulation of peat.

7.4 ENVIRONMENTAL ASPECTS OF CYCLIC SEDIMENTATION IN THE M.I.B.

The existence of a significant transition path through a sequence of lithologies indicates that the sedimentary succession was not laid down in a random fashion. Some systematic mechanism or controls influenced deposition and the order of the lithological changes in the M.I.B.

Earlier workers in the Sydney Basin (Booker, 1960; Loughnan, 1966a; Duff, 1967) noted a vertical pattern in the lithological succession and this has been termed, by some, "cyclic sedimentation" although individual explanations of the phenomenon varied between workers. The results of the Markov chain analysis suggest the sedimentary unit or cycle can be represented by the most probable transition path as determined in Section 4.3 and diagrammed:

$$\begin{tikzcd} \text{Conglomerate} \arrow[r] & \text{Sandstone} \arrow[r] & \text{Claystone} \arrow[r, shift left] & \text{Coal} \arrow[l, shift left] \arrow[lll, dotted, bend left] \end{tikzcd}$$

This would correspond to Duff and Walton's (1962) *modal cycle* for the M.I.B. The cycles are usually developed as fining-upwards sequences overlain by peat horizons both in synclinal and anticlinal regions, and in this Sub-group the frequency of cycles increases in regions of greater subsidence (i.e. some coals and fining-upwards sequences are restricted solely to synclinal areas). Apparently at certain times, probably associated with low net subsidence, fine clastic sediments only were deposited in these synclinal subsidence areas and an environment suitable for limited peat growth ensued. On equivalent horizons in adjacent areas of lower (or at these times zero) net subsidence correlatable claystone units are rarely present although sandy horizons are not uncommon, with little or no evidence to suggest that peat ever formed at these intervals.

Read and Dean (1967) explained their results by suggesting that in areas of maximum subsidence, channels carrying coarse clastic sediments would inhibit the growth of vegetation in the area. In the Macquarie Syncline areas of maximum subsidence display the most favourable conditions for peat formation. However in the vicinity of the Tulliallan Trough, Read and Dean (1967) observed that the number of coal cycles decreases sharply while the total thickness of strata (and hence average cycle thickness) continues to increase. The difference in the relationship for the Tulliallan Trough as compared with the Macquarie Syncline is interesting in that the initiation and development of a favourable environment for organic accumulation is critically tied to the intensity and the nature of the subsidence. The gradients of the best fit lines of the average cycle thickness as a function of total thickness or the number of cycles may be a sensitive measure of this activity.

To the north of the area studied, the Macquarie Syncline in the lower sub-groups shows evidence of an extremely high rate of subsidence similar to that operating in the Tulliallan Trough. North of the Wangi Peninsula the coal seams show an increasing tendency to become split with wedges of sandstone and conglomerate as the structure-low areas of the basin are approached and the total thickness of coal decreases slightly; the percentage of inorganic detritus in the coal increases in these areas (Branagan and Johnson, 1970). Hence the areas which were optimal for peat accumulation are peripheral to the main synclinal axis which contrasts markedly with the situation in the overlying M.I.B. to the south.

The type of cycle development in the M.I.B. may be different in part in origin to the Carboniferous cyclothems of Europe and North America where eustatic or tectonic controls, or both, may at times have influenced deposition with the development of widespread marine phases within someof these cyclothems (Westoll, 1968). It is probable however that limestone-bearing cyclothems can be initiated under similar subsidence conditions (but with a different accumulation balance) to those prevailing during the deposition of the M.I.B.

The cycles in the M.I.B. appear to be largely independent of controls external to the basin and cyclic variation in the succession seems in the main controlled and determined by the inter-relation of sedimentation and tectonics. The cycles themselves could develop as a result of the relaxation of fluviatile processes in the area. In the nomenclature of Beerbower (1964) the cyclothems could be termed *autocyclic*, i.e. generated within the sedimentary system.

Duff *et al.* (1967) consider that sedimentary controls alone are insufficient to explain the generation and repetition of coal-bearing cycles although these controls are regarded by them as the main cause for the interseam successions (in this case fining-up cycles). They suggest (p.154) that periodic flooding of the coal swamp, necessary for the beginning of a new cycle, cannot be brought about solely by sedimentary factors. This flooding, however, need not be initiated by external factors such as tectonic subsidence or eustatic changes, but could occur simply because the swamp vegetation ceased to flourish due to changes in drainage and alteration of the nutritional properties of the layers with the development of oligiotrophic peats (edaphic influences). Elliott (1969) in a review of cyclothem development in the coal measures of the East Midlands, where lower deltaic conditions prevailed also mentions the role of edaphic influences as a mechanism for the cessation of coal-peat accumulation. These edaphic factors were also linked to an increased severity of fungal and bacterial attack on both living and dead vegetation.

Smyth (1966), Smyth and Cook (1973) have shown that the upper parts of the main seams of the M.I.B. are richer in inertinite than the lower parts. The inertinite-rich lithology is not identical with, but could be similar in origin to, the crassidurains, which Smith (1962, 1968) has interpreted as being formed under relatively dry conditions. This environment results in considerable oxidation and, presumably, leaching of the peat with a slowing down in the rate of accumulation, or a situation where the balance of levels can more readily be displaced to permit the accumulation of epiclastics and the initiation of a new cycle.

Elliott (1969) favours the replacement of conventional cyclothem theories by an episodal concept, with the coals being generated as part of the relaxation process of the deltaic sedimentation; peat accumulation is the final relaxation process when the distributive systems ceased to be active in the subdelta regions. He continues that " . . . whether or not peat accumulation completes the relaxation of deltaic sedimentation is likely to depend upon a slow rate of regional subsidence and the extent to which waning sediment transport is able to prepare a surface of very low topographic relief below water only a few feet deep and hence suitable for invasion by swamp vegetation". While the M.I.B. sediments are unlikely to have been deposited in a lower deltaic environment (a low-meandering and possibly braided fluvial environment being more probable) the relaxation process could similarly apply to the M.I.B. cycles with drainage patterns changing outside the area such that sedimentation waned and the area became subject to peat forming processes. Peat accumulation was at least at the rate of tectonic and compactional subsidence preventing flooding as a result of levee crevassing of channels outside the area. Edaphic influences may have been the cause of cessation of plant growth which in turn initiated flooding of the area and a return of a high energy depositional environment in which coarse clastics accreted.

This internal mechanism explains the order of the sediments and the lateral variation. It agrees with the structure of the observed transition matrices for the M.I.B. with channel-switching readily accounting for the fining-upwards cycle followed by the development of a peat stage. From the values of the elements in the fourth row in the transitional matrix, it appears that the new cycles may not be self-initiating with some additional influence being required. The second most likely alternative after coal is the deposition of conglomerate and hence the beginning of the next cycle. Compaction of the peat under an initial coarse clastic deposit, perhaps due to a major flood, could also be a critical factor in permitting the accumulation of further clastics and the development of a further cycle, rather than a continuation of peat.

The greater frequency of oscillating successions in structure-high areas (areas of lower net subsidence during the Permian) indicates perhaps that these areas were subject to less frequent episodes of fine overbank deposits with the main stream axis tending to persist in the axial region of the Macquarie Syncline. This agrees with the simplicity and greater frequency of fining-upwards cycles in the central parts of the basin as against the more complex (and perhaps composite) cycles on the sediment-impoverished structure-high regions within the basin (Fig.4.3). The major coal seams are relatively extensive and most can be traced over the entire area of the Macquarie Syncline permitting "layer-cake" stratigraphic methods to be used for the major units. This could be taken as the cause of cyclicity. However the extreme complexities of intertonguing which might be expected from a channel-switching model may be masked by subsequent compaction so that the continuity of units is more apparent than real. Alternatively it is possible that major changes in sedimentation were associated with the switching of the major channel activity out of, or into, the Macquarie Syncline to or from the neighbouring synclinal areas.

Most of correlation coefficients are statistically significant and have geologically significant interpretations. However they leave at least as much of the variation unexplained as they explain and it seems that more complex models are required to obtain a more complete analysis of the data.

CHAPTER 8

DISCUSSION OF THE TECTONIC CONTROL ON SEDIMENTATION IN THE MOON ISLAND BEACH SUB-GROUP

8.1 PERMIAN SUBSIDENCE PATTERNS IN THE MACQUARIE SYNCLINE

The results of the thickness trend-surface analyses of lithosomes in the Moon Island Beach Sub-group suggest that a persistent pattern of differential tectonic subsidence influenced the net accumulation of both the peats (coals) and the sediments. The tectonic subsidence showed both regional and local features. Superimposed on the background of persistent basement subsidence was the subsidence due to the compaction of earlier formations. Compactional subsidence variations were however, short-lived, and probably only exerted a significant local influence on peat and sediment accumulation.

The nature and role of the persistent tectonic subsidence and the more ephemeral, compaction-induced subsidence in determining the thickness variations of the sediments and coals in the M.I.B. are evaluated below.

A breakdown of the thickness variations associated with the regional and local components for the three widespread coal formations in the M.I.B. is given in Table 8.1.

COMPONENT	STRUCTURE	THICKNESS		
	WALLARAH COAL	WALLARAH COAL	GREAT NORTHERN COAL	(STH) FASSIFERN COAL
Trend 1	0.81*	0.27*	0.23*	0.06*
Trend 2-1	0.12*	0.10*	0.07*	0.05
Residual 2	0.07	0.63	0.70	0.89

TABLE 8.1 Coefficients of determination associated with components of structure and thickness for the three main coals. (*Values are significant at 95% confidence level).

8.1.1 Regional Subsidence

The regional tectonic subsidence may be divided into two components: one, a weak planar component dipping slightly to the northeast, and the other, a synclinal subsidence pattern with a northnortheast axis.

The planar basement subsidence component dips in the reverse sense to the present-day regional structure but strikes parallel to the eastern extension of the Hunter Thrust and to the structural grain of the New England Fold Block north of Newcastle. The synclinal subsidence axis is roughly normal to this direction.

While the present study demonstrates the existence of a persistent differential subsidence over the southern part of the Macquarie Syncline during the deposition of the M.I.B., isopach maps given by Branagan and Johnson (1970) may be interpreted to infer that the Permian synclinal subsidence also extended north towards Newcastle along the axis of the present-day Macquarie Syncline. Their data are from units in the lower sub-groups in the Newcastle Coal Measures indicating that the particular subsidence geometry probably persisted along the general axis of the Macquarie Syncline throughout the deposition of the Newcastle Coal Measures. Furthermore the thickness variations of the Narrabeen Group sediments which overlie the M.I.B. in the area studied, also show an apparent control by the same synclinal subsidence. The regional subsidence pattern which now coincides with the Macquarie Syncline, probably extended at least from Wyong, in the south, to Newcastle and controlled sedimentation in both the Newcastle Coal Measures and the Narrabeen Group. A lack of data prohibits any further extrapolation of the same structure-thickness relationship to the underlying sediments and coals.

Regional subsidence in the Macquarie Syncline area during the Permian would have been brought about by the combined effect of downwards basement movement and broad-scale compaction of the sedimentary pile. While regional compaction may be of importance in determining net rates of sedimentation (e.g. Morgan, 1970), the recurrence of antiform thickness trends in the units of the M.I.B. suggests that the persistent differential subsidence component is probably due to differential basement movement. Regional compaction perhaps only contributes a minor, and geographically constant proportion of the overall regional net subsidence. It is only at a local scale that compactional subsidence becomes an important thickness determining factor (e.g. see trend results of Eleebana Formation and Great Northern Coal, Sections 5.4.5 and 5.4.6).

The regional synclinal subsidence was not necessarily expressed as a discernable topographic feature as the rate of sediment accumulation during the deposition of the M.I.B. would have at least kept pace with the subsidence. The mean rate of subsidence would probably have been relatively slow with the synclinal character originating and being maintained through a slightly greater rate of downwards movement along the axis of the present-day Macquarie Syncline. The regional subsidence together with the rate and direction of sediment influx is however important in creating the intra-basin palaeogeography and palaeoslope directions. The palaeoslopes and palaeodrainage directions and their relation to the Permian regional subsidence in the Sydney Basin are discussed below in Section 8.2.

8.1.2 Local Subsidence

Local thickness variations of the units in the M.I.B. result largely from two mechanisms. Persistent differential basement subsidence over restricted areas (i.e. local) accounts for the greater part of the meaningful, subsidence-controlled thickness variation. Superimposed on the persistent differential basement movement were local ephemeral subsidence zones which at various times exerted significant, but short-lived influence on the sediment (or peat) accumulation.

Persistent local differential subsidence patterns are generally reflected in the local variation of the present-day structure of the Macquarie Syncline. Along the axis of the regional differential subsidence (now preserved as the Macquarie Syncline) a distinct pattern of local downwards movement occured. There was a tendency for the areas coinciding with the present-day structural features (*vide* Fig. 6.1) of the Chain Valley Depression and the Wyong Slope to subside at a slightly greater rate than the intervening area across the Wyee Saddle. Flanking these areas were domains whose subsidence patterns contribute both to the regional and local components: that is, the areas along the Morisset Anticline and the Swansea Rise which, during the deposition of the M.I.B., were subsiding at a relatively slower rate than the adjacent domains along the regional synclinal subsidence axis.

These local tectonic subsidence domains generally maintained their relative rates of subsidence throughout the accumulation of the peat and clastic horizons of the M.I.B. However the thickness of a given formation is also influenced by a large number of other factors which may locally complicate the net rate of accumulation. It can be seen from Table 8.1 that for the widespread coals a large proportion of the thickness variation is not attributable to regional trends but to local influences. Of this local thickness variation, a significant part can be explained by local tectonic control. That proportion of the variation not explained by local tectonic subsidence, may be due to sedimentological influences (including peat oxidation) and other factors not directly related to differential basement movement. In certain instances a significant proportion of the local subsidence may also include a contribution from an ephemeral subsidence pattern which would be related to differential compaction rather than tectonic control.

Ephemeral subsidence patterns developed as a result of early differential compaction of formations which show major facies variations. These subsidence patterns were added to the persistent background of basement subsidence and caused local, short-lived increases in the relative rate of sediment (or peat) accumulation. The influence of these ephemeral patterns waned as the substratum compacted under the load of the overlying sediment (or peat) and the local differential tectonic subsidence resumed its dominant role. In the M.I.B. ephemeral subsidence domains developed as a result of facies variations in the Eleebana Formation. These subsidence domains are directly reflected in the local thickness variations of the overlying Great Northern Coal.

The Eleebana Formation varies from a fine conglomerate in west of the area studied, to medium and fine sandstone in the central part of the area. In the far north, northwest and south sediments of the Eleebana Formation are composed solely of fine micaceous claystone and constitute overbank phases of deposition. The claystone facies does not appear to be related to the persistent subsidence domains. In areas where the fine facies are developed the Eleebana Formation readily compacted under the weight of the organic debris of the encroaching forest-swamp of the Great Northern Coal. This early compaction resulted in a relatively greater rate of local subsidence over the claystone facies than over adjacent areas where the swamp was underlain by the non-compacting coarse facies. The subsidence pattern induced by early differential compaction is reflected directly in the thickness variations of the overlying Great Northern Coal (*vide* Sections 5.4.5 and 5.4.6 and Figs. 5.18 and 5.21). However before the cessation of peat accumulation the rate of compaction of the claystone of the Eleebana Formation declined and the regional and local tectonic subsidence again began to influence significantly the peat accumulation. Hence the compaction-induced subsidence was short-lived but was locally important in determining the development of the peat horizon.

As a further evaluation of the influence of ephemeral subsidence it may be useful to study in detail the intra-seam stratigraphy of the Great Northern Coal. Such a study could provide an insight into the mechanism and importance of ephemeral, compaction-induced subsidence.

8.2 PERMO-TRIASSIC SUBSIDENCE PATTERNS IN THE SYDNEY BASIN

The trend-surface analyses of the units in the M.I.B. established that Permian subsidence geometry is, in certain respects, directly manifest in the present-day structure of the Macquarie Syncline. Structures of similar form to the Macquarie Syncline traverse the Sydney Basin and contribute to a complex regional component superimposed on the broad-scale, simple saucer-shape structure of the basin. These structures may also be present-day intensifications of earlier Permo-Triassic subsidence patterns.

In order to establish the geological validity of extrapolating the structure-thickness relationhsip to other areas of the Sydney Basin the results of Cook (1969a) from a study of structure-thickness relationships in the Bulli Seam on the Southern Coalfield may be compared with those from the M.I.B. Palaeoslope directions and their relation to regional subsidence in the Sydney Basin are evaluated in the light of both these studies.

Geological field evidence is introduced below to support the hypothesis of the contemporaneous activity of these structures and their possible relationship to earlier sedimentation (Middle and Lower Permian) in the Sydney Basin.

8.2.1 Comparison of the Macquarie Syncline and the Southern Coalfield Structure-Thickness Relationships

Cook (1969a) in a study of the thickness variations of the Bulli Seam in the Southern Coalfield also established a relationship between the seam thickness and the present-day structure. Using trend-surface analysis he isolated regional and local components in the structure and thickness data and found that the subsidence patterns during the accumulation of the Bulli Seam are related directly to the present-day structure. The absence of significant conglomeratic facies changes in the sediments of the Illawarra Coal Measures (Wilson, *in* Packham, 1969) would suggest that ephemeral subsidence patterns due to differential compaction had little or no influence on the peat accumulation of the Bulli Seam. Thus regional and local thickness variations are due largely to tectonic basement subsidence.

The regional homoclinal structure trends in the Southern Coalfield vary inversely with the planar thickness trend of the Bulli Seam. This is in contrast with the Macquarie Syncline where the regional subsidence was probably greater to the north in the reverse sense to the present-day homoclinal dip. This reversal is due largely to upward movement of the New England Fold Block along the Hunter Thrust System in post-Triassic time with the dip of the Permian strata increasing rapidly towards this fault zone. The relationships between planar subsidence patterns and the palaeoslope directions are discussed in the proceeding section.

Although the planar components of structure and thickness are differently related in the Southern Coalfield and the Macquarie Syncline the pure synclinal components and the local components in both area show similar inverse relationships. Also by inference from the results of Cook and Sheils (1968) and the general parallelism of the results of Cook's (1969a) work with those of the trend analyses of the M.I.B. formations (apart from the homoclinal components), it would seem probable that regional and local differential subsidence features persisted throughout the late Permian and Triassic and similarly influenced other formations in the Southern Coalfield. Cook and Sheils (1968) show a cover map for the Bulli Seam which, because of their selection of data, is virtually an isopach map for the interval from the Bulli Seam to the top of the Hawkesbury Sandstone. This cover map shows a close similarity with the geometry of the fourth degree structure trend map presented by Cook (1969a) and the thickness variations of the particular interval have obviously been controlled by the same differential subsidence pattern as that which influenced the Bulli Seam accumulation.

As most of the fold-like structures in the Sydney Basin have a similar geometry and probably formed at the same time (Raggatt, 1938) it is likely that the regional and local components of these structures would be related to the thickness variations of the late Permian and Triassic formations in other parts of the basin.

8.2.2 Regional Subsidence and Palaeoslope Directions

(a) Permian Palaeoslope Directions

During the late Permian, clastic detritus was largely derived from the New England Fold Block and transported into the northern part of the Sydney Basin in south flowing streams. This sediment transport direction is indicated by current bedding directions and fossil log orientation in the Newcastle Coal Measures (Diessel, 1968) and supported by the distinctive detrital rock fragment lithologies of the sandstones and conglomerates in the late Permian Hunter Valley sediments. In the south and west of the basin during the deposition of the Illawarra Coal Measures sediment transport directions were generally from the south and west respectively (Herbert*, *pers. comm.*)

The coarse modal grain size of the sediments in the M.I.B. indicates that alluvium was transported probably in braided river systems flowing south from the northern hinterland and draining into the piedmont fluviatile plain of the Sydney Basin. The geometry of the conglomerate fans and the grain size and facies gradients (Pryor, 1961) confirm this general palaeoslope direction for the M.I.B.

In contrast to the south-dipping palaeoslope during the M.I.B. deposition, the trend results of the present study suggest a planar regional subsidence in the opposite sense to the palaeoslope direction. Cook's (1969a) regional subsidence for the Southern Coalfield dipped to the north and in sympathy to the sediment transport directions for that area. Figure 8.1 is a diagrammatic representation of the regional subsidence and palaeoslope profiles across the Sydney Basin from the Southern Coalfield to the Newcastle

*1973, N.S.W. Dept. Mines.

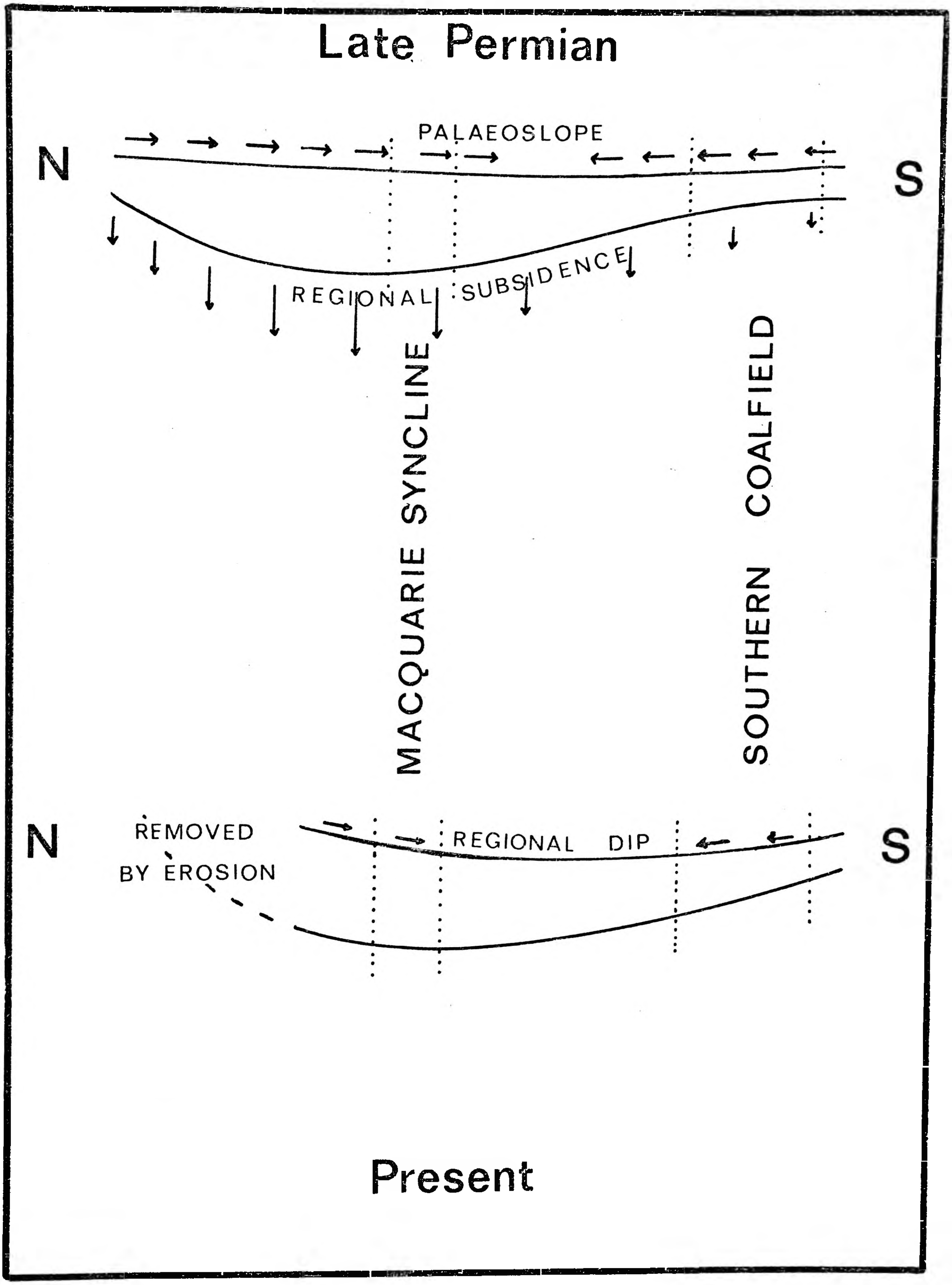


FIGURE 8.1 Conceptual model for the Late Permian subsidence geometry and palaeoslope directions and their relationship to the present structure. Section is approximately north-south along eastern side of Sydney Basin.

Coalfield during the late Permian. Close to the Hunter Thrust Zone regional subsidence increased but due to the high volume of sediment influx did not alter the direction of the south-flowing tributary system.

In the northern part of Sydney Basin it would seem that the rate of sediment supply greatly exceeded the rate of subsidence and thus sediment supply rather than regional subsidence determines the palaeoslope. Elsewhere in the basin (south and west), although the rate of deposition still exceeded the rate of subsidence, the rate of sediment supply per unit of depositional area would have decreased in towards the centre of the basin due to the increasing area to be fed by the limited quantity of sediment. This effect, combined with a relatively greater rate of subsidence in the northern and central parts of the basin than in the marginal southern and western areas, would have controlled the drainage patterns in the late Permian. The palaeoslope in the northern part of the basin would result from an oversupply of sediment in the maximum subsidence area close to the New England Fold Block and a lesser amount of available sediment to be deposited over a larger area (i.e. central part of the basin) such that southerly grading of the streams would occur.

Thus in the Hunter Valley the Permian palaeoslope is not directly related to the tectonic subsidence. Rather sediment supply is the governing parameter.

(b) Triassic Palaeoslope Directions

During the early Triassic the palaeoslope in the northern part of the basin continued to dip to the south with the Narrabeen Group sediments also largely derived from the New England Fold Block. However there is a significant change in the character and the composition of the Munmorah Conglomerate (Narrabeen Group) as compared with the underlying clastic sediments of the Moon Island Beach Sub-group.

Plate 2.12 shows a section of green sandstone of the Karignan Conglomerate Mb. overlain by lighter coloured sandstone of the Munmorah Conglomerate. The sandstones and conglomerates of the Newcastle and Singleton Coal Measures generally are relatively devoid of plutonic quartz and contain a significant quantity of unstable volcanic detritus which has broken down to chloritic clays (hence the green colour). However the immediately overlying sandstone shows a considerable increase in plutonic quartz and a complimentary decrease in the unstable volcanic fraction; the quantity of chert and acid volcanics remains unchanged. Further the maximum grainsize of pebbles in the Munmorah Conglomerate is only 3 cm whereas the maximum grainsize in the coal measure conglomerates is of the order of 15 to 10 cm.

There is, therefore, a sudden increase in the maturity of the sandstones and perhaps a slight change of provenance from the Newcastle Coal Measures to the Narrabeen Group.

A major reversal of palaeoslope occurred at the end of the deposition of the Narrabeen Group with the overlying Hawkesbury Sandstone being deposited from the south and southwest of the Sydney Basin (Standard, 1964). This unit may have extended well to the north over part of the senile peneplained hinterland and across the present-day line of the Hunter Thrust. This palaeoslope direction was probably the result of uplift of the southern hinterland and a lack of tectonic activity to the north of the basin.

While the planar regional subsidence pattern in the Hunter Valley area may have changed in the Triassic the complex regional subsidence geometry probably was maintained with the thicknesses of the Triassic sediments generally reflecting the late Permian basement subsidence patterns.

Although not directly relevant to the palaeoslope directions of the Permo-Triassic sediments it is convenient to mention at this stage the climatic changes which may have occurred from the Permian to the Triassic. The increased maturity of the Narrabeen Group sediments as compared with those of the Newcastle Coal Measures may be partly due to a slight increase in chemical weathering in the source areas.

Early workers (e.g. David, 1907) assumed the late Permian coal measures to have accumulated in a cold climate (on the basis of a lack of sediment oxidation and the existence of coal seams). The presence of red beds in the

Narrabeen Group sediments was considered to indicate a warm, leaching environment (Loughnan, 1963) thus suggesting that a major climatic change took place at the end of the Permian. Recent palaeontological work yields conflicting evidence for the late Permian climate. Riek (1972) considers the insect assemblages in the Newcastle Coal Measures to be indicative of a cold climate, while Gould (1972) considers that a mild, temperate climate prevailed. Loughnan (1963, 1972) using mineralogical evidence favours a temperate to warm climate. On balance it would seem that a temperate climate without severe winters may have prevailed during the late Permian.

The Triassic climate is considered by Loughnan (1972) to have probably been a warm, leaching environment on the basis of red bed sediments (up to 25% Fe_2O_3) and well-ordered kaolinite in the Narrabeen Group Formations. Cook (*pers. comm.*) has observed the presence of minor vitrinite in these red beds suggesting that extreme oxidising conditions are unlikely. Although the palaeoclimates of the Sydney Basin are still poorly understood, a marked change from the Permian to the Triassic is evidently unlikely. Rather a slight change of emphasis in a temperate climate took place with slightly warmer conditions in the Triassic would account for the observed lithological differences.

During the early Triassic increased weathering in the source areas and during transportaion would lead to a decrease in unstable detritus with a concomitant increase in stable material. However the increase in plutonic quartz may also be related to the influx of detritus from the initial erosion of the extensive batholiths of the New England area.

8.2.3 Some Field Evidence Supporting the Contemporaneous Activity of Basin Structures

Raggatt (1938) in a study of the structural evolution of the Sydney Basin was the first to suggest the relationship between the present-day 'folds' and the thickness variations of the Triassic sediments although he attributed much of the folding to Tertiary horizontal compression. The most marked of these structures is the Lochinvar Anticline which extends south from Cessnock as the Kulnura Anticline (mapped and named by Raggatt, 1938).

This structure developed during the early part of the deposition of the marine Mulbring Siltstone of the Maitland Group. Subsequently, and until the deposition of the Narrabeen Group, the area along the Lochinvar Anticline persisted as a non-subsidence zone with a major lacuna being present. Thus the Mulbring Siltstone is only represented by its lowest member (Muree Sandstone Mb.) and the upper coal measures are absent. The alternative explanation for this lacuna: that these strata were deposited and later eroded in the late Permian or early Triassic with the development of the structure taking place at the onset of Narrabeen Group sedimentation, is not apparently supported by field observation (Raggatt, 1938). Such an event would entail the rapid erosion of at least 1000m of sediment and severe erosional structures at the top of the Muree Sandstone Mb. would be expected. These structures are not present and the apparent thinning, rather than truncation of the coal measures on the flanks of the Lochinvar Anticline supports the former hypothesis.

Farther south on the Kulnura Anticline a thin, impoverished coal measure sequence is developed indicating that the non-subsidence was restricted to the northern part of the structure. While the coal measure strata thin and disappear approaching the Lochinvar Anticline the pre-Mulbring Siltstone sediments apparently do not show thickness variations relatable to the structure. Such an absence of any structure-thickness relation in the older sediments would suggest that the Lochinvar Anticline may have not existed previous to Mulbring Siltstone times as a significant controlling structure. During the Triassic the area ceased to form a non-subsidence zone but still did not subside at the rate of the adjacent synclinal areas as the Narrabeen Group and the Hawkesbury Sandstone both reflect the structure in their thickness variations.

The area along the Lochinvar Anticline probably exerted a major influence on the palaeogeography and drainage patterns within the basin during the late Permian. It is not possible to correlate satisfactorily the Newcastle and

Tomago Coal Measures with the Singleton Coal Measures although attempts have been made (e.g. Britten, 1968). The area along the structure may have provided an effective barrier between sub-basin areas with fluvial-swamp conditions prevailing more or less independently on both sides of the area. This ridge may have had some influence on primary drainage patterns and stream avulsion which, in turn, would affect whether swamp conditions or an influx of coarse detritus occurred in the sub-basin areas.

Branagan (1960) in a study of the sedimentation in the Western Coalfield presented isopach maps for some formations over the marginal part of the basin which show an obvious regional tectonic control related to the present-day structure. These results lead Branagan to conclude similarly to Raggatt (1938) that much of the folding in the Sydney Basin is associated with the Permian subsidence geometry.

Evidence of the existence of contemporaneous deformation in the Southern Coalfield has been presented by Cook and Johnson (1970). Amongst the field examples of such deformation they describe the occurrence of regularly jointed intraclasts of sideritic claystone in breccia-filled washouts in sandstones immediately overlying the Bulli seam at Coalcliff on the Southern Coalfield. The blocks of closely jointed clay-ironstone have been derived by contemporaneous erosion of adjacent thin beds of clay-ironstone. However while the conjugate joint frequency in both the undisturbed pavement and the intraclasts are identical, the jointing in the intraclasts are in random orientation from block to block. Thus obviously, the jointing of the clay-ironstone pavements took place prior to the local contemporaneous erosion which resulted in the deposition of jointed slabs of the ironstone in the nearby washout structures.

It is interesting to note also that the joint directions in the undisturbed pavements are the same as those in both the host Narrabeen Group sandstone and the overlying Hawkesbury Sandstone in this locality.

The evidence provided by the jointed 'ironstone' intraclasts appears to indicate the quite unequivocally a very early origin for these joints. The vertical persistence of the jointing directions would support the hypothesis that a major contemporaneous stress field influenced sedimentation and remained more or less unchanged at least until lithification of the Sydney Basin sediments was complete.

8.3 POST-TRIASSIC DEFORMATION IN THE SYDNEY BASIN

The results and data presented in Chapter 6 and in the above section have established that the present-day structure of the Sydney Basin is an intensification of the basement subsidence patterns which controlled deposition during the late Permian and Triassic. Except for part of the

Hunter Valley and possibly along the coastal margins of the Sydney Basin, the homoclinal dip component of the regional structure as well as the complex fold component are a simple manifestation of the earlier regional subsidence. It has further been established that the local subsidence domains are also preserved in the present-day structure.

Faulting and jointing are the only other structural deformations apart from the slight intensification of the regional subsidence, to have occurred in the Sydney Basin. However, as Cook and Johnson (1970) have shown, the jointing in much of the Sydney Basin is likely the product of the earlier stress fields associated with tectonic subsidence being maintained. Jointing of much of the Sydney Basin probably took place during the final stages of the structural intensification and when the sediments were lithified.

Blayden (1971) in an analysis of the joints and faults in the Macquarie Syncline concluded that the "fold was formed during the Cainozoic from a minor episode of lateral compression acting in a westnorthwest direction and not during the Hunter-Bowen Orogeny at the end of the Permian". This conclusion is in contrast to the results presented here which indicate that the structure is more likely a result of Permo-Triassic differential subsidence geometry. The role of the Hunter-Bowen Orogeny in the evolution of the structure is not clear; it may have initiated the basement failure patterns at the beginning of Mulbring Siltstone and may have exerted a continuing influence.

Blayden used isopach maps of three of the four sub-groups in the Newcastle Coal Measures (including the M.I.B.) in attempting to detect a relationship between thickness and structure. The apparent absence of such a relationship is understandable since it is not possible when using thickness data of composite units (i.e. sub-groups) to take account of the compaction effects of units comprising a number of different lithologies. This is especially so when the section includes rapidly deposited conglomerates, major facies variations, or the development of restricted and split coal seams. The trend analysis results presented here (*viz.* the anomalous results obtained for the Teralba Conglomerate Mb. thickness) and other studies (e.g. Wermund and Jenkins, 1970, on sandstone facies in the Pennsylvanian of Texas) more than show the need for the analysis of thickness variations to be confined to single rock units.

As one of the sub-groups analysed by Blayden was the M.I.B. and, in view of the results obtained for the M.I.B. in this study, the conclusion reached by Blayden (1971) would appear to be incorrect. It should be pointed out that many of the joint directions determined by Blayden are directly related to the Macquarie Syncline structure but this does not affect the argument. The joints could equally well have developed during the Permian as at a later stage.

An early origin may also be postulated for much of the faulting in the Sydney Basin. The most prominent of the faults is the Kurrajong Fault which runs north-south along the west side of the basin with a displacement varying from 0 to 300m. The fault parallels, and more or less coincides with a Permo-Triassic hinge zone across which a major regional thickening in towards the basin occurs. Most other faults are of much lower displacement with throws up to 75m but most being of the order of 5 to 10m. Hanlon (1953) and Johnson (1968) give examples which have throws decreasing from the Permian to the Triassic indicating that much of the faulting may be contemporary faulting of the type described by Westoll, *in* Murchison and Westoll (1968) from the Carboniferous coal measures of northern England. Also Cook (1969a) shows that the Bulli Seam locally thickens on the downthrown side of the Bulli Fault.

Post-Triassic igneous activity broadly falls into three categories:

(i) undersaturated doleritic intrusions (sills and laccoliths)

(ii) saturated basalts (flows, necks and dykes)

(iii) breccia-filled diatremes.

The first group were emplaced mainly during the Jurassic and are usually large laccolithic bodies of near-saturated composition. They probably occur across most of the Sydney Basin and are not necessarily confined to any particular stratigraphic interval. They are frequently intersected by deep bores in the central part of the basin. One such body, the Warrawolong Dolerite, occurs to the west of the Macquarie Syncline emplaced in Narrabeen Group sediments. These bodies may cause local doming due to upward displacement of the country rock. Cook (1969a) noted effects on structure residuals which probably were attributable to such bodies emplaced at depth below the Bulli Seam. However these bodies have no affect on regional trends.

The majority of igneous bodies in the Sydney Basin fall into the second group. They include small dykes emplaced along old joints, breccia and basalt necks (usually a few hundred metres across) and residuals of basalt flows. They are younger than the former group and age determinations range from late Cretaceous to late Tertiary (Joplin, 1964). No extraneous structural deformation can be attributed to these intrusions. During this later phase of activity a certain degree of simple uplift occurred resulting in the present elevation of the basin.

8.4 SEDIMENTATION OF THE M.I.B. UNDER THE INFLUENCE OF AN ACTIVE DIFFERENTIAL SUBSIDENCE ENVIRONMENT

It has been established in Chapters 5 and 6 that the thicknesses variations of units within the M.I.B. were influenced by regional and local patterns of differential basement subsidence. The subsidence patterns were not as simple as might be envisaged from the present-day structure and varied geographically and in their degree of influence on the sedimentation of clastic formations and the accumulation of peat. Local ephemeral subsidence frequently caused significant complications to the general patterns of subsidence which combine with sedimentological and climatic influences to control the rate of accumulation of sediment (and peat) and the preservation of this sediment. The sedimentation of the M.I.B. formations is discussed here to indicate the dynamic role of other physical parameters such as sedimentation rates, superimposed on a background of differential subsidence in determining the ultimate thickness of these formations.

Prior to discussing the history of sedimentation in the M.I.B. it is necessary to briefly consider some of the causes of the initiation of the peat swamp environment, its continuation and its eventual termination in order to account for the differences in the strength of the relationship between coal thickness and present-day structure.

8.4.1 Initiation, Continuation, and Termination of the Peat Swamps of the M.I.B.

The origin of the coal of the M.I.B. in this study has been assumed to be autochthonous. A number of workers (e.g. Duff, 1967) have disagreed with this view pointing out the

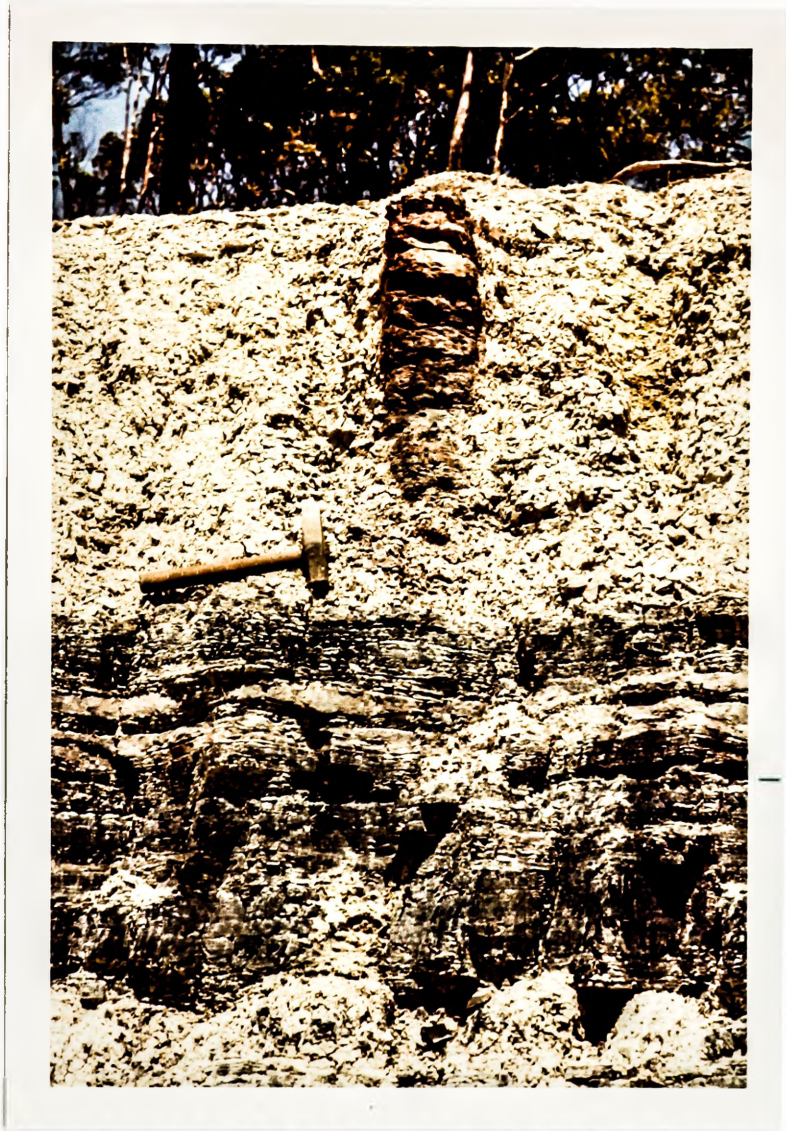


PLATE 8.1 Small fossil tree in position of growth at top of South Fassifern Coal, Mawson.

absence of characteristic seat-earths. However the formation of peat horizons at the top of fining-upwards cycles would seem to indicate a genetic relationship between the waning of depositional energy and the onset of swamp conditions. Also the field evidence of an autochthonous origin is unequivocal. For example Plates 8.1 and 8.2 give evidence of *in situ* growth of vegetation in the peat swamp of the South Fassifern Coal at Swansea. Plate 8.1 shows a small fossil tree stump (20cms in diameter and 90cms high) "growing" from the roof of the seam, while Plate 8.2 shows a polished slab of coal from the same locality with a root preserved as vitrinite obliquely traversing the "bedding". Both of these examples are difficult to explain with an allochthonous model. The comparative rarity of such marked cross-cutting by plant roots is explicable in terms of the large compaction ratio. Indeed it seems probable that much of the vitrinite at least has been derived from *in situ* plant roots. This would accord with the findings of Spackman *et al.* (1969) for modern peats in the Everglades.

The initiation of peat swamp conditions is directly dependent on the waning of high energy clastic deposition in the sub-basin area. The decline in clastic sedimentation may have resulted either from the incipient colonisation of the floodplain by a forest-swamp vegetation which prevented further flooding or from stream avulsion in the main fluvial drainage system caused perhaps by a lowering of stream

PLATE 8.2 Vitrinised root traversing the "bedding" of the South Fassifern Coal. x1

gradients due to sediment choking in the sub-basin area. The invariable occurrence of a fining-upwards cycle beneath each of the coals of the M.I.B. and the slightly greater frequency of fining cycles over coal cycles would suggest that the vegetation phase is not in itself responsible for the fining cycle and the waning of clastic deposition.

With the establishment of the peat swamp which colonised (and stabilised) the floodplain the net rate of accumulation of the organic detritus was similar to the rate of subsidence of the substrata (both compaction of earlier sediments and downwards movement of the basement). An accumulation balance is achieved between the rate of floral growth (and the retarding rate of organic oxidation) and the rate of subsidence. The rate of growth in such swamp conditions must be capable of exceeding the rate of subsidence in order to prevent flooding and destruction of the swamp environment through a widespread influx of clastic detritus. The oxidation rate of the peat would increase rapidly for organic debris which was substantially above the water table where aerobic fungae and bacteria would thrive. Hence a competitive balance in the rate of accumulation of the peat (the preserved organic fraction) is maintained such that the rate of accumulation of the peat closely parallels the rate of net subsidence in the swamp.

It is interesting to note that the coals of the M.I.B. contrast with those of the lower sub-groups in containing fewer dirt bands and a lower proportion of vitrinite. This observation suggests that a different accumulation balance prevailed during the M.I.B. The M.I.B. peats were more subject to oxidation and those of the lower sub-groups were more subject to inundation by overbank floodwaters.

The main constituent of the accumulated body of peat is water included in the fibrous peat mass. This results in the bulk density of the peat being very close to that of water. As a function of the low density of the peat the rate of compaction of the peat during this swamp phase is both slow and decreases with depth. Hence for example the (South) Fassifern Coal which may vary in thickness from 5 to 10m and using a net compaction ratio of 10 to 1 (Elliott, 1969) a contemporaneous peat thickness of up to 100m may have perhaps existed. At the base of the peat section (where fine clastics are abundant) the peat would have compacted to some extent with excess water being partly expelled during the physical and chemical breakdown of the organic debris during this early stage. The degree of compaction would decrease exponentially towards the surface with the uppermost part being a weak, water-logged mass of floral debris providing a root base and nutrient source for the prevailing forest-swamp.

Mineral nutrients for the swamp vegetation would be provided from the breakdown of suspended detritus in the water normally flowing in the swamp and also from occasional minor overbank flooding which resulted in the development of thin veneers of claystone intermittently through the section. However it seems probable that the peats became more oligotrophic with increasing thickness and that the amount of new organic material available gradually declined. The change in the edaphic characteristics of the peat was probably accompanied by floral changes (Smith, 1962; Smith *in* Murchison and Westoll, 1968; Smyth, 1972). The Bulli Seam is similar in many respects to the coals of the M.I.B. and it has been suggested by Johnston and Cook (1969) that peat ablation was a major factor contributing to the lithological character of the Bulli Seam. The closing phases of peat accumulation may therefore have been associated with high rates of peat loss due to oxidation and a stunted flora.

The suspended minerals entering the swamp undoubtedly had a marked effect upon plant growth and peat lithology (Smyth, 1972) with vitrinite-rich coal commonly occurring above dirt bands. The mineral content of many of the major coals is relatively high, being of the order of 15% in many instances. It could be argued that such high proportions of inorganic material should have provided adequate nutrition to support high rates of formation of organic debris. Two factors militate against this argument. Firstly allowing for a compaction ratio of 10:1 the original content of mineral matter would have been less than 1% on a volumetric basis and secondly it probably only reached as high a level as this due to oxidation of much of the available organic material (see above).

The maintenance of the swamp conditions was dependent on both the absence of significant clastic sedimentation and a continuation of subsidence coupled with an inhibition of the organic decay process. Hence as Spackman *et al.* (1969) point out in a study of modern peat environments in Southern Florida, the formation of laterally accreting and geographically extensive authochthonous coal seams "requires the interaction of certain biological phenomena in a geological situation that is dynamically adjusted to provide for the accumulation of plant debris with a continual maintenance of the geochemical conditions requisite for such accumulation". While the warm, paralic conditions prevailing in such modern swamps can not be directly equated with conditions which may have been cooler and an environment more similar to a limnic basin, the work of Spackman *et al.* shows the sensitivity of swamp environments to subtle variations in drainage, substratum lithology, and elevation in terms of living floral assemblages and the floral composition of the peat.

The cause of the termination of peat swamp conditions is not clear. Depletion of mineral nutrients and increased fungal attack may have led to a slowing of vegetation accumulation to a rate below the rate of subsidence with the result that avulsion and capture of the drainage systems occurred which lead to flooding and renewed fluvial sedimentation. An alternate explanation is that stream avulsion was initiated as a result of the lowering of stream gradients in an adjacent sub-basin area. However it is difficult to envisage that the gradients in the swamp would be greater or even equal to those in a maturing fluvial regime. Further the occurrence of erosional remnants of claystone overlying some of the coals (e.g. Great Northern Coal and the Wallarah Coal) would suggest that prior alluvial deposition in the area was subject to overbank low energy flooding after the termination of peat swamp conditions. Overbank flooding was a relatively common event in the swamps of the Newcastle Coal Measures, as shown by the widespread occurrence of claystone horizons in some seams and was not in itself likely to terminate floral growth. It would seem more probable that this later overbank flooding was a result of continued subsidence in the swamp area where vegetation had ceased to flourish and accumulate.

Although some of the evidence provided by the analysis of the M.I.B. cycles might suggest the coal swamp was terminated by an abrupt change in areas of high energy deposition it would seem that the waning of swamp conditions was at first associated with biological constraints and later with resultant stream avulsion and clastic sedimentation.

Another hypothesis that may be offered as an explanation of peat swamp termination is that flooding may have occurred as a result of minor uplift in the source areas (or accelerated downwards movement in sub-basin). Inferences from the results of the cycle analysis would tend to indicate that such a model is unlikely for the autocyclic (Beerbower, 1964) M.I.B. sequences.

8.4.2 M.I.B. Sedimentation

The peat accumulation of the Fassifern Coal (and the South Fassifern Coal) began to take place with the waning of clastic deposition in the Macquarie Syncline sub-basin area. Fining-upwards sequences are developed on the sandstones and conglomerates at the top of the Boolaroo Sub-group with the base of the (South) Fassifern Coal characterised by an intercalated sequence of thin coal, carbonaceous shale and claystone. The claystones represent the final stages of overbank low energy flooding across a newly vegetated area where the swamp flora soon flourished and minor episodes of fine clastic deposition became more infrequent.

The peat of the (South) Fassifern Coal accumulated at a pace governed by the net subsidence at each point across the area and since the supply of sediment (mainly organic) exceeded the subsidence the swamp growth was able to maintain a stable and more or less constant base level in the sub-basin area. Hence any moderate differential downwards movement is reflected in a local increase in the quantity of peat preserved. As a consequence the (South) Fassifern Coal shows weak but significant regional and local thickness variations which can be related to the present-day structure. This pattern is however complicated by variations in the degree of coal development at the base of the seam as well as by the large clastic wedge of the Doyalson Formation and inconsistencies in definition arising from this formation.

The swamp conditions of the (South) Fassifern Coal were interrupted for a short time by renewal of clastic deposition and the influx of medium and coarse-grained alluvium which makes up the Doyalson Formation. The geometry of the Doyalson Formation is consistent with a northerly source yet it is difficult to account for the zero isopach for the formation to the north. This thinning is closely defined across the south end of Lake Macquarie and if the Doyalson Formation does extend further north along the Macquarie Syncline axis it would be as a narrow channel zone less than a kilometre in width. A lack of subsidence further north may have prevented widespread deposition of the conglomerates with the result that the sediment was transported further south in narrow channels where it was deposited in broad fans across the peat swamp. The complex patterns of the thickness variations suggest that the streams were braided with inter-channel islands apparent in the isopachs and the facies variations. The material transported in this possible stream system along the east side of the area studied was also deposited to the southeast in the vicinity of Moon Island. To the west of this channel a separate drainage system is apparent from the isopachs of the Doyalson Formation and must have drained from the northwest into the southern part of the area. The confluence of these two drainage systems is reflected in the spur shape of the zero isopach line. Also conglomeratic material is less common in the southern and western parts of the area fed by the western distributary system. Inter-channel islands are evident from restricted areas of overbank sediment (Fig. 5.14) in the southern part of the area.

The location of the channels and islands while not directly controlled by basement subsidence has been indirectly influenced by the compressability of the underlying peat. The compressability of the peat was probably a direct function of the thickness of that peat which in turn is partly related to subsidence patterns and it is likely that the channel directions were controlled by the immediate compaction of the peat under the weight of the conglomerate alluvium. It should be noted that the strength of peat is such that bar-finger sands can form by compaction of the peat but not normally by the rupture of the peat. The inter-channel islands of fine sediment were probably the result of the same process with the South Fassifern Coal at the localities having an high proportion of clastic sediment in the section. Along the margins of these channel systems adjacent to the undisturbed swamp of the Fassifern Coal thick sections of fine sediment were deposited in quiet areas peripheral to the main channel. Any basement subsidence which occurred during the relatively rapid deposition of the Doyalson Formation would have had a minimal effect on the thickness variations of this unit. The space for the sediments of the Doyalson Formation need not have been created by basement movement but could simply result from the contemporaneous compaction and dewatering of the peat substratum due to the increment of relatively dense inorganic clastic deposits.

In the swamp marginal to the area of clastic deposition vegetation continued to flourish and with the waning of sedimentation encroached and spread over the entire area again with the limited peat development of the Chain Valley Coal.

Towards the end of the development of the Chain Valley Coal low energy clastic sedimentation (Eleebana Formation) began to occur from the northwest (as indicated by facies gradients, (Pryor, 1961)) and spread over the entire area. Along the west side of Lake Macquarie fine conglomerate was deposited (presumably a channel zone) and to the north east and south facies changes occur. North of the area of fine conglomerate only claystone sediment was deposited, the area forming a reverse bypass zone. This claystone facies extends to the east and thickens and becomes more sandy, while the conglomeratic zone itself gives way in the Newvale area to medium-grained sandstone. In the far south this outwash fining from the relatively small conglomerate fan is apparent as a widespread area of claystone.

The Eleebana Formation does not seem to have been influenced in its channel patterns by the variations in the immediately preceding formations although the rate of differential subsidence has partly controlled the local thickness variations in regard to the finer facies. The facies variation within this formation coupled with the subsequent variations in compaction have complicated the analysis of this formation and show that it may be preferable to restrict such analysis to discrete lithosomes. However the present treatment of this formation has revealed very close relationships between its lithology (and compaction ratio) and the development of the overlying coal. Subsequent to the deposition of the sediments of the Eleebana Formation, widespread but moderate diagenesis under high pH conditions took place in the sandstones and claystones with the development of analcite and secondary silica phases and the development of a cherty texture. The sodium in the analcite was probably derived from the breakdown of feldspathic detritus in the fine sediment.

A number of workers have considered these cherty rocks as tuffs (e.g. Loughnan, 1966b) and ascribed the analcite to the breakdown of volcanic glass. In many of these rocks there are suggestions of shard-like shapes in thin and polished sections, but these may simply be interstitial areas between sand grains (*vide* Plate 2.1a and b). Further the common occurrence of cross-bedding and other related sedimentary structures in many of these so-called "tuffs" is likewise inconsistent with the abundance of the apparent "shards"; such fragile pyroclastic material would be unlikely to survive transport. There is no other evidence of vulcanicity in the Newcastle Coal Measures and while the present author does not reject *in toto* the possibility of tuffaceous rocks in the Newcastle Coal Measures it is felt that there is insufficient evidence at this stage for the term to be applied to these rocks.

The peat swamp of the Great Northern Coal which spread over the area following the cessation of clastic deposition of the Eleebana Formation was characterised by a lack of overbank flooding with only a very few geographically restricted claystone bands being present in the seam. The change from clastic sedimentation to swamp conditions occurred relatively quickly with no alternating claystone-coal sequence being developed at the base of the seam. During the earlier stages of the peat swamp an ephemeral subsidence pattern associated directly with the compaction of the underlying Eleebana Formation exerted both a local and regional control over the quantity of peat which could accumulate.

Areas of swamp with a sub-stratum of wet clay and silt sediment experienced a greater net peat accumulation apparently due to the additional subsidence resulting from the continuing compaction from the overlying peat mass. On the other hand the thinner and poorer quality Great Northern Coal often occurs over the coarse facies of the Eleebana Formation which did not compact under the weight of the peat and hence shows a far slower rate of peat accumulation possibly due to a higher rate of peat oxidation. This higher rate of oxidation is indicated by a higher proportion of included mineral matter in the coal in these areas (based on proximate analyses, Joint Coal Board) so that a high mineral matter can in this case be considered a remanié feature rather than one directly associated with depositional processes.

These ephemeral subsidence patterns lessened in their influence as the underlying sediment became more compact and gradually the background basement subsidence resumed their dominant control over the regional and local rate of net peat accumulation. Hence the present-day thickness of the Great Northern Coal may be related both to the thickness and lithology of the Eleebana Formation as well as to the present-day regional and local structure. It would be of interest to acquire intra-seam details of the Great Northern Coal and study the relationship between the seam stratigraphy and the lithological variation of the underlying Eleebana

Formation to more closely assess the role of compaction-induced subsidence.

The period of peat accumulation of the Great Northern Coal was followed by the deposition of fine clastic sediment over the area. However the original extent and thickness of the claystone was probably greater than the present occurrence since it appears to occur as erosional residuals, the bulk (i.e. >> 50%) of the sediment having been removed during the initial deposition of the Teralba Conglomerate Mb.

The sediment forming the Teralba Conglomerate Mb. was transported by streams which were probably flowing from the north and northwest (based on isopach geometry, facies gradients and sediment composition) into the sub-basin area. Compaction of the upper part of the peat of the Great Northern Coal would have accommodated the initial blanket of coarse alluvium such that only relatively slight stream grading would have occurred. The energy necessary for the transport of the pebbles would be generated by local development of high gradients through stream choking. Due to the ease of compaction of the underlying peat lateral accretion by channel wandering would have taken place readily during flood periods. Most of the conglomerate was *transported* as an in-channel phase similar to the fluvial models outlined by Visher (1965) and Leopold *et al.* (1964) but *deposited* as channel levees and point bar sheets.

These workers give data which show that the rate of sediment accretion due to lateral migration of channel systems is far greater than that due to vertical accretion by overbank sedimentation. This observation is supported by the lithological nature of the Teralba Conglomerate Mb. in which very little clay-size overbank sedimentation has been preserved. Much of the fine sediment in the Teralba Conglomerate Mb. occurs as channel infillings deposited during periods of lower stream velocity rather than true flood plain deposits.

Three main phases of deposition of the Teralba Conglomerate Mb. occurred separated by the periods of restricted peat accumulation of the Buff Point Coal Lens and the Toukley Coal Lens. At the top of each phase fining-upwards sequences of sediments are present in the axial region of the Macquarie Syncline and these have been generated as a part of the fluvial lateral accretion process (Visher, 1965) and preserved as sedimentation temporarily waned. Restricted peat accumulation was probably geographically influenced by differential subsidence along the axial region of the present-day Macquarie Syncline which stabilised and preserved the underlying fine sediment. Renewal of alluvial sedimentation may have partly eroded the unprotected overbank sediment peripheral to the peat lenses or the fine sediment may have had a restricted development initially. While regional and local tectonic subsidence patterns were no doubt active during the deposition of the Teralba Conglomerate Mb. they may not have been of sufficient intensity to influence significantly the thickness of the conglomerate horizons. During the pauses in clastic sedimentation, which may have occupied more time than the depositional periods, peat accumulation may have been sufficiently slow to show the differential subsidence. The conglomeratic alluvial blanket fanned across the area of the Macquarie Syncline and extended south to the vicinity of the Wyee Saddle where the conglomerate thins rapidly. Further south the Teralba Conglomerate Mb. is represented by a few metres of sandstone which may be regarded as an outwash phase of the coarse high energy sedimentation. The sudden facies change is perhaps related to a very low rate of subsidence across and south of the Wyee Saddle which resulted in a choking of the area and a diversion of coarse sediment to another area where higher stream gradients prevailed. The lowering of energy in the Macquarie Syncline area and the resultant diversion of the alluvium to another sub-basin area is supported by recent drilling results (unpublished records, Metals Investment N.L.) on the west flank of the Kulnura Anticline to the northeast of Sydney. A thick conglomerate horizon of similar grain-size and composition to that of the Teralba Conglomerate Mb. was intersected below the top coal seam of the upper coal measure sequence. It may well represent an associated or subsequent alluvial fan of the same phase of deposition as the Teralba Conglomerate Mb. This western conglomerate fan extends 50km further south than that of the eastern Macquarie Syncline area.

With the final waning of deposition of the conglomerate a fining-upwards cycle developed during the final accretion phase and the fine member of this is preserved as the Mannering Park Claystone Mb. The rate of deposition of this fine clastic sediment was sufficiently slow for the thickness variations to be influenced by the regional and local basement subsidence patterns with the thickness components correlating with the present-day structure of the Macquarie Syncline area. Swamp vegetation rapidly stabilised the area and peat began to accumulate in a fashion similar to the other widespread coal formations in the M.I.B.

The rate of accumulation of the Wallarah Coal was closely governed by regional and local subsidence patterns similar to the present-day structural components. In the far south over the sandy facies of the Teralba Conglomerate Mb. a high rate of oxidation, as evidenced by the thin, shaly coal sequence, prevailed due perhaps to the differences in compactional subsidence offerred by the thick conglomerate and the thin sandstone horizons. Peat swamp conditions of the Wallarah Coal were terminated by renewed clastic sedimentation to form the Karignan Conglomerate Mb. which is of a similar character to the Teralba Conglomerate Mb. but this clastic unit was restricted to the axial region of the

Macquarie Syncline and to the north of the more slowly subsiding Wyee Saddle area.

The final coal swamp environment of the Newcastle Coal Measures was locally developed over the Karignan Conglomerate Mb. sediments as two thin coal horizons termed the Vales Point Coal Mb. This episode was probably short-lived and terminated by an influx of sandstones and fine conglomerates of the Munmorah Conglomerate together with a probable warming of the climate which may have been a factor reducing the chances of any subsequent accumulation of major peat deposits. On the flanks of the Macquarie Syncline area the Munmorah Conglomerate river system partly eroded fine-grained Newcastle Coal Measure sediments overlying the Wallarah Coal (possibly an overbank phase of the Karignan Conglomerate Mb.). The reworked sandstones common at the base of the Munmorah Conglomerate (*vide* Plate 2.12) and the restricted extent of these claystones are indicative of this subsequent erosion.

8.5 SEDIMENTATION AND TECTONIC ACTIVITY: GENERAL

For widespread terrestrial or shallow marine sedimentation to continue over a long period and for the products of the deposition to become preserved as part of the sedimentary record it is necessary for the underlying basement to subside and accommodate the sediment volume. While such mechanisms may be considered axiomatic in a broad-scale sense the role of *differential* basement subsidence patterns is open to some dispute. The argument is also complicated by the debatable effect of the sediment weight in perpetuating and controlling the basement subsidence.

In the Sydney Basin the question arises as to whether structural patterns within the basin were the result of differential rates of subsidence that were caused by sediment loading or whether the differential rates of subsidence were the result of tectonic stress that caused structural patterns and controlled sedimentation. During the mid-Permian a basement failure pattern developed which persisted throughout later Permo-Triassic sedimentation and was perhaps initiated as a response to structural activity in the Tasman Geosyncline during the closing stages of the Hunter-Bowen Orogeny (Brown *et al.*, 1968). It is unlikely that sediment loading would have been sufficiently regular to produce the persistent patterns of anticlinal-synclinal subsidence which traverses the Sydney Basin (Branagan, 1960; Cook, 1969a,b). During the deposition of a given sequence such as the M.I.B. subsidence of the basement was at least temporarily accelerated along pre-existing movement patterns. For example the Teralba Conglomerate Mb. was not significantly controlled in its thickness variations by independent basement subsidence since the normal rate of tectonic subsidence would be much less than the rate of sedimentation. On the other hand the standing mass of incompactable conglomerate may have downwardly displaced itself through compaction of the underlying, less dense strata but it is difficult to account for displacements with an amplitude of the order of 50 m by this process alone. In the far south in the Wyong Slope area only slight subsidence occurred as evidenced by the thin, equivalent sand facies of the Teralba Conglomerate Mb. which is locally developed indicating there was perhaps some degree of perpetuation of channel areas in response to the early differential compaction of the underlying strata. The weight of conglomerate could however, have initiated a certain degree of basement movement in areas where it was being developed with a resultant resistance to subsidence taking place further south. During extended pauses in the alluvial deposition of the Teralba Conglomerate Mb. independent basement movement probably only influenced the low energy clastic sedimentation and the restricted peat accumulation. In any event it is likely that both compactional subsidence and subsidence initiated by sediment load operated to influence the deposition of the Teralba Conglomerate Mb.

Isostatic principles can be used in evaluating the possible role of sediment-induced basement subsidence patterns. It is variously argued that for marine sedimentation the load on the basement increases with sedimentation since the water (S.G.1) is displaced by sediment (S.G. approx. 2) and as a direct result downward of the basement occurs. Weimer (1970) invokes this argument in accounting for the existence of a contemporaneous rising structure which formed between, and parallel to, two centres of deltaic sedimentation in the Upper Cretaceous of Wyoming. However regional tectonic subsidence independent of sediment load did also occur in that area. It is possible that the density contrast of the Teralba Conglomerate Mb. (perhaps with a Permian bulk density of 2.5) and the underlying coal measure strata (? less than 2.0) may have been sufficient to cause localised isostatic adjustment but the low density and greater volume of peat establish that if this process was operating it would be restricted to dense, thick and rapidly deposited formations.

For example isostatic adjustment from sediment loading is virtually untenable in the case of thick, widespread autochthonous peat horizons which probably had a bulk density very close to 1 and thus was of lower density than that of the underlying strata. Hence differential basement subsidence during periods of peat accumulation could only be generated as a result of tectonic stresses operating over the area of the Sydney Basin and not in response to variations in sediment-load. The results of the trend-analyses of the widespread coal units of the M.I.B. provide empirical confirmation of this mechanism in showing that the coals best reflect a consistent regional and local basement subsidence pattern in their thickness variations. As the net peat accumulation was sensitive to the differential subsidence which prevailed during the late Permian it follows that this close relationship was largely created as a function of the long period of time over which peat swamp environment extended. During the formation of the M.I.B. peat swamps dominated the area with fluvial clastic deposition being a relatively uncommon phenomena temporarily interrupting the slow accumulation of peats.

The influx of coarse and medium-grained detritus occurred as a result of changes in the drainage patterns which lead to channel-switching into the Macquarie Syncline sub-basin area. The shift in clastic deposition may have been initiated by tectonism in the source areas which altered the patterns of hinterland erosion. Tectonic movement in the hinterland of the Ganges-Brahmaputra delta has lead to modifications to the channel-systems and changes in the area of sedimentation (Morgan, 1970). This worker also points out that sedimentation in the Ganges delta is controlled by a series of normal basement faults and movement of these is probably independent of the sediment load. An alternative mechanism is that channel-switching is self-generated as a result of maturing of episodes of clastic deposition and a lowering of stream gradients through choking of channels such that flooding occurs and new tributary systems are developed in adjacent areas thereby blanketing the peat swamps in these areas. The widespread development of simple fining-upwards cycles and the overall similarity of the clastic detritus in the Newcastle and Singleton Coal Measures tend to favour the latter model as does the presence of systematic intra-seam lithological sequences (Smyth, 1972). Hence south-draining streams which may have been characteristically low-meandering to braided in their form, carried sediment into the northern part of the Sydney Basin but varied in their activity at any time.

The lateral continuity of the coal horizons in the basin is more apparent than real and is a result of a process of lateral accretion of the coal swamp and the long periods over which uninterrupted swamp environments prevailed. Hence separate areas of peat development could ultimately merge with phases of clastic sedimentation slowly spreading across the swamps and laterally accreting so that they also form continuous horizonal strata. The subsequent compaction and coalification of the peat horizons resulted in the thicknesses of coal and clastics presenting a reversal of the relative time taken to accumulate the strata and emphasise the "layer-cake" aspect of the lithosomes.

The present-day thickness of coal horizons has unfortunately lead many workers in the Sydney Basin to ignore the important role of differential basement subsidence patterns on the accumulation of the peat and the formation of the coal.

CHAPTER 9

CONCLUSIONS

Using statistically-based methods it is possible to analyse the structural and thickness variations of formations in the Moon Island Beach Sub-group into meaningful regional and local geological components of variation. The study of the relationships of these components for the major lithosomes of the M.I.B. has shown that a consistent pattern of differential basement subsidence prevailed during the deposition and accumulation of the sediments and peats. The persistent tectonic subsidence influenced the rate of coal accumulation such that similar regional antiform thickness components are present in the thickness isopleth maps of the three widespread coal seams of the M.I.B. Similar regional thickness trends are also present in a number of the clastic formations especially the finer grained sediments. At a local scale tectonic subsidence patterns combined with the compactional subsidence of the underlying strata to influence the rates of accumulation of both coals and sediments with the result that areas exhibiting relatively faster and slower rates of subsidence were superimposed on the synclinal subsidence pattern.

The activity of these contemporaneous basement subsidence structures resulted in substantial early deformation of the sediments in the basin. The present-day structure of the area studied,and indeed of the Sydney Basin, is essentially an intensification of the late Permian subsidence structures. The Macquarie Syncline, apart from the homoclinal dip in towards the central area of the Sydney Basin, is a direct expression of the regional tectonic subsidence pattern which determined the antiform thickness trends in many of the units of the M.I.B. A number of local elements of the present-day structure have been isolated as residual components of the regional structure of the Macquarie Syncline. They include the Chain Valley Depression and the Wyong Slope, locally depressed areas in the axial zone of the Macquarie Syncline, with the Morisset Anticline and the Swansea Rise flanking this zone as structurally-positive anticlinal areas. Separating the depressed areas of the Macquarie Syncline is a transverse ridge-like feature referred to as the Wyee Saddle which locally complicates the regional structure. All of these present-day local structural domains are manifest in the thickness variations of many of the lithosomes in the M.I.B. although other sedimentological and minor changes in rates of subsidence tend to mask, but not obliterate the relationship.

The homoclinal dip in the northeast part of the Sydney Basin does however not appear to represent an intensification of the planar subsidence which operated during the late Permian. Rather the present dip is probably a reversal of the contemporary planar subsidence with the area towards Newcastle subsiding at a slightly faster rate than that to the south. However the planar subsidence was at a very low gradient and was not sufficiently rapid to influence the palaeoslope or the drainage directions of the south-flowing streams. Sediment derived from the metasediments, acid volcanics and granites of the New England Fold Block to the north of the Sydney Basin was transported into the Macquarie Syncline sub-basin area in fluvial-braided streams. Sandstones and conglomerates were deposited over relatively short periods of time and maintained a "topped-up" state in the basin with stream gradients to the south being developed as a result of the lower volume of sediment being available for deposition further downstream. Consequently a palaeoslope which dipped to the south prevailed during sedimentation and was not affected by planar regional subsidence patterns.

During periods of peat swamp growth the rate of net peat accumulation closely kept pace with the subsidence and no significant palaeoslope gradients developed. The peat swamps probably laterally accreted from a northerly direction and spread southwards across a veneer of fine clastic detritus deposited as fining-up cycle which formed on the coarser, high energy sediment during the waning and maturing of the preceding depositional cycle.

While tectonic subsidence patterns exerted a consistent influence on the rates of accumulation, ephemeral subsidence domains which developed as a result of rapid early compaction of fine clastic sediment relative to adjacent areas of coarse detritus also played an important, but short-lived role in determining thickness variations of the immediately overlying peat horizon. However these ephemeral subsidence patterns faded in their effect as soon as the incipient compaction of the underlying was complete and the tectonic subsidence resumed its omnipresent role in determining regional and local thickness variations.

The mean rate of accumulation of a given unit is probably the most important physical parameter in controlling the extent to which that formation reflects the prevailing tectonic subsidence pattern. Hence thick, widespread coal units which accumulated over a long period of time were sensitive to the slight and infrequent downward movement of the basement and show a higher correlation between present-day structure and thickness than do the detrital formations. The clastic sediments were deposited more rapidly than the peat accumulated and their thickness variations were less closely related to the minor patterns of the differential tectonic subsidence.

The sediments and coals of the Moon Island Beach Sub-group were deposited with a tendency to develop a specific lithological sequence which was a product of the sedimentary environment. Within the lithological sequence of the M.I.B. cycles may be identified. Generally the cycles may be considered as depositional episodes which were initiated by changes in drainage system with coarse clastic being deposited from low-meandering braided streams over a compacting substratum of wet peat. As the sub-basin area became choked with sediment the depositional energy waned and a veneer of medium and fine-grained sediment, deposited as a floodplain phase, was preserved and a fining-upwards cycle developed. Vegetation stabilised the low energy floodplain and organic debris accumulated at a rate which more than kept pace with the subsidence; oxidation maintained an accumulation balance such that a high water table prevailed. In this manner a coal-bearing cycle was generated. The peat swamp environment was terminated by renewed flooding caused by channel switching outside the area perhaps partly initiated by edaphic influences operating in the swamp which inhibited further growth.

The trend-surface analyses of the units of the M.I.B. has highlighted the need to restrict the thickness variable to individual lithosomes; formations composed of a number of different lithologies are difficult to analyse and interpret satisfactorily as variations in compaction ratio cannot readily be taken into account. Also by treating individual lithosomes a minimal range of depositional energy is considered when attempting to determine relationships between the ultimate thickness and the sedimentary tectonic environment.

In view of the similarity of the structures in the Macquarie Syncline area with those in other parts of the Sydney Basin and the results of Cook (1969a) it is reasonable to draw two conclusions which are probably applicable to much of the Sydney Basin. These are:

(i) That a significant pattern of differential tectonic basement subsidence prevailed during the deposition of the late Permian coal measures and persisted during the deposition of the Triassic sediments. The pattern of relative differential movement was perhaps initiated during the last phase of marine sedimentation (Muree time) and subsequently exerted a varying degree of influence on the thickness of sediment accumulated over the area of the Sydney Basin. Both regional and local components of the thickness variations are identifiable and may be related to contemporaneous tectonic subsidence patterns.

(ii) That post-Triassic deformation of the Sydney Basin, apart from minor faulting has been simply an intensification of the pre-existing patterns of differential subsidence. The present-day structure of the Sydney Basin is a direct manifestation of the Permo-Triassic basement movement. The north-south open folds which traverse the Sydney Basin, like the Macquarie Syncline, reflect the complex regional contemporary subsidence components, with the synclines being domains of greater net subsidence.

As the subsidence patterns persisted throughout the late Permian and Triassic the present-day structure of the Hawkesbury Sandstone and Narrabeen Group may be used to deduce relative thickness information of the coal measure sediments, and in particular of the widespread, coal seams (these being the most closely related to present-day structure). Hence detailed structural mapping of the Triassic sediments and trend-surface analysis of these data to establish the probable regional and local (Permian) subsidence domains may result in considerable economies in prospecting the central part of the Sydney Basin where a thick (Triassic) cover is present.

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